WITH THE AUTHORS COMPLIMENTS.

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New York State Museum

JOHN M. CLARKE, Director

Museum Bulletin 146

GEOLOGY OF THE NEW YORK CITY (CATSKILL) AQUEDUCT

STUDIES IN APPLIED GEOLOGY COVERING PROBLEMS ENCOUNTERED IN EXPLORATIONS ALONG THE LINE OF THE AQUEDUCT FROM THE CATSKILL MOUNTAINS TO NEW YORK CITY

BY
CHARLES P. BERKEY

ALBANY

UNIVERSITY OF THE STATE OF NEW YORK

1911

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New York State Education Department
Science Division, April 6, 1910

Hon. Andrew S. Draper LL.D.
Commissioner of Education

SIR: The extraordinary engineering operations which have been undertaken in the effort to provide the city of New York with an adequate water supply have illuminated in most unexpected manner the geological structure and history of the region of the Hudson valley south of the Catskill mountains. So broad has been the scientific scope of this engineering problem and so direct its dependence on geological structure that the Commissioners of the New York City Board of Water Supply early found it of essential moment to enlist in their service a corps of trained geologists.

In 1909 an agreement was effected between the Board of Water Supply and the State Geologist, in pursuance of which the geological data acquired in the preliminary and final surveys for the aqueduct were intrusted to Dr Charles P. Berkey, a member of the staff of the board as well as of the geological survey, for summation and presentation of their broader and more important bearings.

I transmit to you herewith Dr Berkey's report thereupon, entitled *Geology of the New York City (Catskill) Aqueduct.* It is a document of high value not only in enlarging and perfecting our knowledge of the geological structure of the commercial center of the United States, but its data and conclusions must prove of profound importance to all large engineering and architectural propositions concerned with the region of the lower Hudson valley.

I therefore submit this, subject to your approval, for immediate publication as a bulletin of the State Museum.

Very respectfully

JOHN M. CLARKE

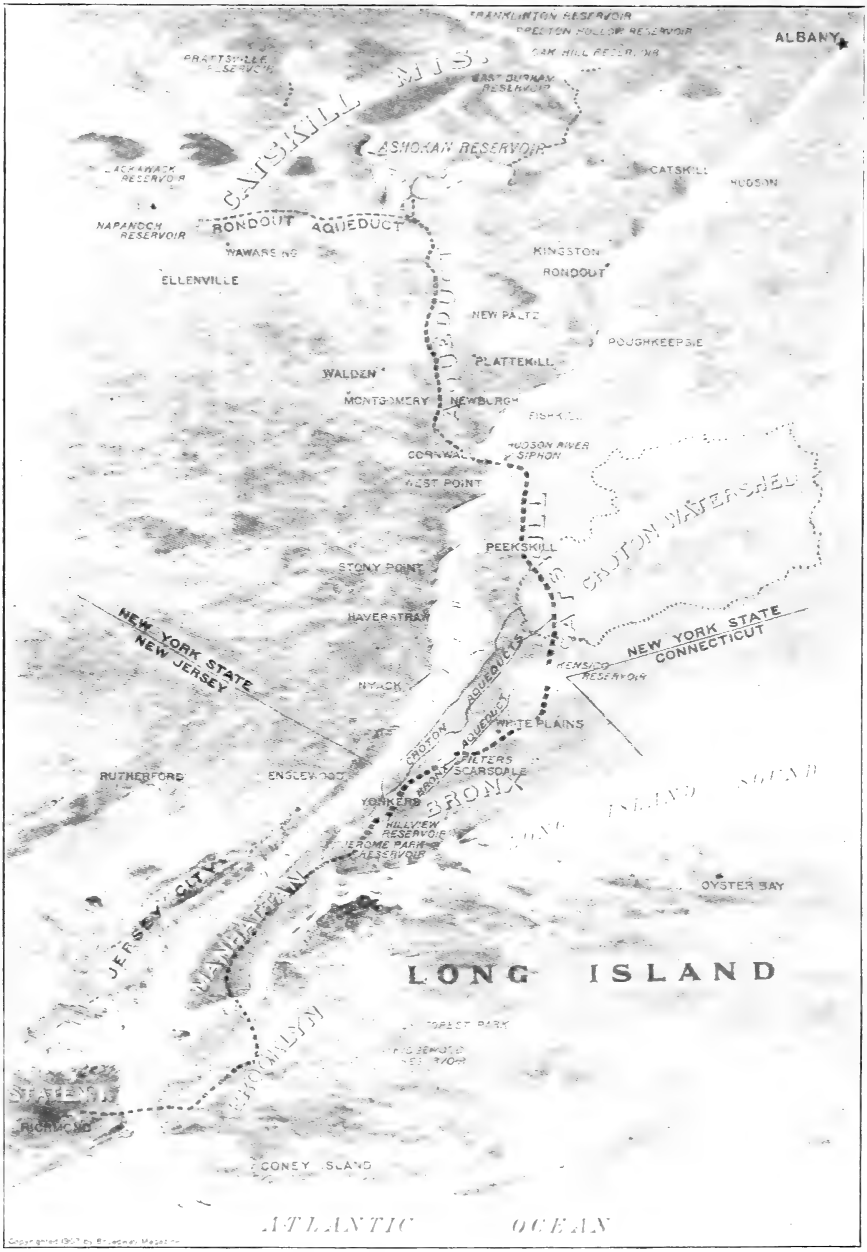
Director

State of New York
Education Department
COMMISSIONER'S ROOM

Approved for publication this 7th day of April 1910

Commissioner of Education

Plate I



The Catskill and Croton water supply systems of New York city

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BY

CHARLES P. BERKEY

INTRODUCTION AND ACKNOWLEDGMENT

It is the writer's hope that the series of studies brought together in this bulletin may help to effect a wider appreciation of the practical usefulness of geology. The volume contains a summary of the local geologic facts and the general principles found helpful in solving some of the problems encountered in a single great engineering enterprise. The summary is accompanied by brief discussions of the methods employed and of the final results or conclusions reached. It is therefore essentially a study in applied geology.

Seldom has so favorable an opportunity been afforded to follow extensive exploratory work and check geologic hypothesis or theory by subsequent proof. And still more seldom have engineers in charge of similar works so fully appreciated the value of geologic investigations and the extent to which they can be utilized as a guide.

More credit is due to Mr J. Waldo Smith, chief engineer of the Board of Water Supply of the City of New York, than to any one else for appreciating the importance of the geologic complexity of

the Catskill Aqueduct problem. His exceptional insight into its nature led to the adoption of measures in this direction that are now proved to have been fully justified. A staff of geologists has been maintained. From time to time engineers of the regular staff who have shown unusual aptitude in such investigations have been assigned to special duty on geologic exploratory work. In the preliminary investigations of the Northern Aqueduct, Division Engineer James F. Sanborn was very intimately connected with the geologic work. With him the writer worked out many field studies that later formed the basis of advisory reports, covering locations, kinds of explorations to be made, and interpretations of data. No one has had a better grasp of both the geologic and the engineering aspects than Mr Sanborn. It is with great pleasure that the writer acknowledges many valuable suggestions and much help through association with him. In the later exploratory work within the city similar service has been rendered by Mr John R. Healey, who has much to do with the geologic detail of the delivery conduit data. The consulting geologists employed by the board were Professors James F. Kemp, W. O. Crosby and the writer.

A special debt is acknowledged to Prof. James F. Kemp, consulting geologist of the board, whose confidence in the writer's work originally brought him into touch with these investigations as an assistant, and with whom since that time many joint reports to the board have been written.

Valuable advice and assistance in arranging for the issue of this report has been given by Department Engineer Alfred D. Flinn of Headquarters Department. For some of the corrections and suggestions special acknowledgment is made to Department Engineer Thaddeus Merriman.

The department engineers, Robert Ridgway of the Northern Aqueduct, Carlton E. Davis of the Reservoir, Merritt H. Smith, formerly of the Southern Aqueduct, Frank E. Winsor of the Southern Aqueduct, William W. Brush and Walter E. Spear of the City Delivery have given every facility for gathering geologic data within their territory and have contributed largely to the better understanding of their special fields.

The geologic matter relating to special problems has been worked out with the aid of the division engineers in direct charge in the field. Among these must be mentioned L. White of the Esopus division, William E. Swift of the Hudson river division, A. A. Sproul of the Peekskill division, Lawrence C. Brink of the Wall-

kill division, J. S. Langthorn of the Ashokan reservoir, Wilson Fitch Smith of the Kensico division, T. C. Atwood of the New York city delivery division.

The data included in the tabulation of this bulletin have been gathered largely by others. Many of the explanations and conclusions are the outgrowth of the work of engineer and geologist, together. A large number of associates are engaged on this public work in such relations to one another that the individuality of each is obscured in the common effort to reach an enviable efficiency and success for the whole enterprise.

The combined efforts of many, unselfishly given, have thus brought together a total far in excess of what any one individual could accomplish. Acknowledgments should therefore be made to those members of the staff of the Board of Water Supply who can not in the nature of the case be mentioned by name. Were it not for their cooperation the great mass of data here summarized could not have been compiled.

CHARLES P. BERKEY
Special Geologist, New York State Geological Survey;
Consulting Geologist New York City Board of Water Supply
Columbia University, New York City November 1, 1910

I

GENERAL FEATURES

CHAPTER I

CATSKILL WATER SUPPLY PROJECT

New York city obtains its chief water supply from the Croton river watershed. Other sources[1] now drawn upon are less important although some of them, such as the Long Island underground supply, are capable of considerable additional development. The average daily consumption of Croton water was approximately 324,000,000[2] gallons for 1907. At the present rate of increase of population the consequent daily increase in consumption of water is 15,000,000 gallons in each succeeding year.

The entire daily flow of water in the Croton river for the 18 years from 1879 to 1897 averaged only 348,000,000 gallons. About 10,000,000 gallons per day is lost by evaporation and seepage from existing reservoirs. The records for 40 years, from 1868 to 1907 make a somewhat better showing. Making no allowance for evaporation the average flow amounts to 402,000,000 gallons. With due allowance for evaporation,[3] however, this only increases the daily supply as now planned by about 47,000,000 gallons. That is, the possible total additional water within the Croton watershed would suffice for only three years' growth of the city. Much of this additional water belongs to periods of excessive precipitation. To save it would require additional storage facilities for 305,000,000,000 gallons, and, it is estimated, would probably cost $150,000,000.

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[1] Brooklyn is in part supplied by these additional sources which furnished 145,000,000 gallons daily in 1907.

[2] The figures used here as to consumption and capacity and available supply are taken from the printed statements of the commissioners of the New York City Board of Water Supply in a circular dated April 16, 1908, and are based upon the investigation and reports of the corps of engineers headed by J. Waldo Smith, chief engineer, John R. Freeman and William H. Burr, consulting engineers. The reports of this commission and various others that have had the responsibility of investigating the future supplies for New York city have been drawn upon freely for such data.

[3] The average rainfall for the past 40 years is about 49 inches per year. Only about 48 per cent of this runs into the streams. The rest evaporates or is absorbed by the vegetation or joins underground supplies that do not again appear at the surface in the district.

Taking into account the small relief possible in this direction and the certainty that in less than five years the demands of the city will be greater than the total capacity of the Croton watershed, it is clear that some other source of large and permanent supply is an absolute necessity.

In the search for such additional sources, there has been much careful work done by able commissioners.[1] In the meantime, residents of certain districts where there are possible supplies have taken steps by legislative action to effectually[2] prevent New York city encroaching upon their territory. Criticisms[3] of all kinds largely by those only partially informed as to the magnitude and complexity of the problem and partly by those ignorant of the simplest factors in its solution, have been kept perpetually before the public. One needs only a slight acquaintance with such public works to realize that it is much easier and more common to criticize and raise the cry of corruption or incompetence than it is to give really valuable advice or solve a real problem or carry an enterprise of the most vital public importance to a successful issue.

It is sufficient here to observe that exhaustive studies of the whole question of water supply by competent men have resulted in a practically unanimous conclusion that the streams of the Catskill mountains are the most satisfactory, economical, reliable, abundant and available future source of water.

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[1] The Report of John R. Freeman C. E., 1899-1900; Report of the Burr-Herring-Freeman Commission, 1902-4; the Studies of the Department of Water Supply, Gas and Electricity, 1902-4; Investigations of the Board of Water Supply, 1905 to the present time.

[2] Acts of the Legislature of 1903-4.

[3] The commonest suggestions neglect the question of permanence or constancy of supply. The following sources are often mentioned, (*a*) Lake George, forgetting that this beautiful lake has an abnormally small watershed and could never figure as a large permanent supply; (*b*) artesian wells, ignoring the fact that with the exception of certain portions of Long Island there is almost no artesian capacity, and on Manhattan and the mainland the crystalline rocks make such development useless; (*c*) Lake Ontario, apparently overlooking the great distance (400 miles) and the many other complications that this international water body involves; (*d*) the Housatonic river, neglecting the difficulties of interstate origin; (*e*) Dutchess county, where the city is prohibited by legislative enactment; (*f*) the Hudson river, ignoring the fact that the Hudson is an estuary of the sea with brackish water of a very impure quality and wholly unfit for domestic uses. It is, however, worth while to note that Hudson river water is sure to be used more and more extensively for fire protection and similar purposes in the more densely populated portions of the city by means of an entirely different system of conduits. This is one of the most promising directions of relief looking to the more distant future.

The Catskill supply will furnish over 500,000,000 gallons of water daily and was estimated to cost $161,857,000. That is, the additional supplies from the Catskills as planned will, when completed, be sufficient for the increasing demands of the growing city, for the next 35 years. And some of it may be badly needed long before it can possibly be delivered.

Parts of the Catskill system[1]

The chief sources within the Catskills now included in the plans of the board are:

1 Esopus creek, to be taken at a point near Olive Bridge.

2 Rondout creek, to be taken at a point near Napanoch.

3 Three small streams tributary to the Rondout.

4 Schoharie creek, to be taken at a point near Prattsville.

5 Catskill creek, to be taken at a point about 1 mile northeast of Durham.

6 Six small streams tributary to the aqueduct between Catskill creek and Ashokan reservoir.

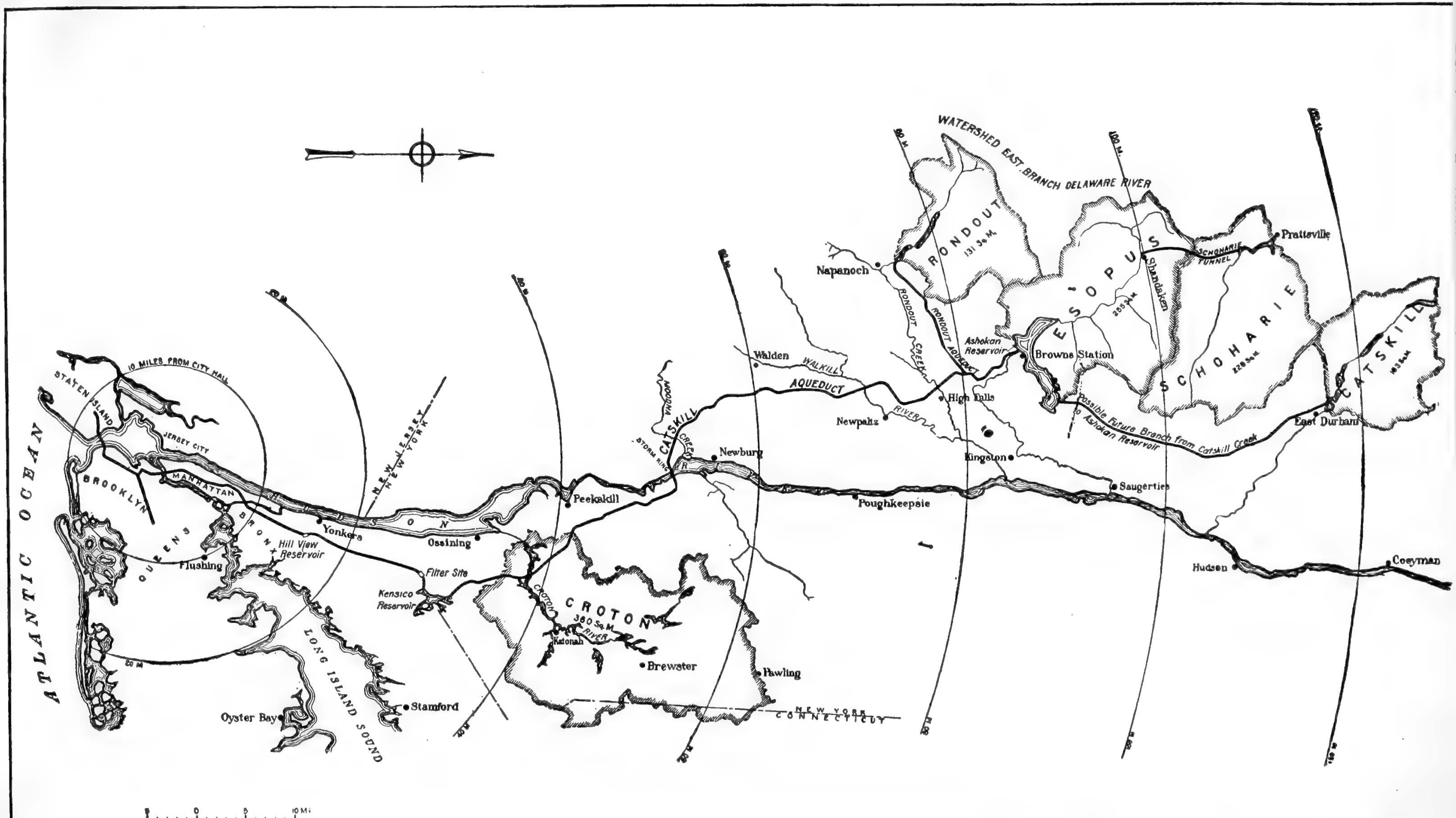
The comparative areas of watershed and their daily capacity are estimated[2] by the corps of engineers as follows:

	AREA IN SQUARE MILES	STORAGE IN GALLONS	DAILY SUPPLY IN GALLONS
1 Esopus watershed	255	70 000 000 000[3]	250 000 000
2 Rondout watershed	131	20 000 000 000	98 000 000
3 Three small tributaries	45	....	27 000 000
4 Schoharie watershed	228	45 000 000 000	136 000 000
5 Catskill watershed	163	30 000 000 000	100 000 000
6 Six small streams	82	....	49 000 000
Total	904	165 000 000 000	660 000 000

[1] The subdivisions and proposed locations given here are taken chiefly from the Report of the Board of Water Supply of the City of New York to the Board of Estimate and Apportionment, October 9, 1905.

[2] Estimates are much more complete for the Esopus, which it is planned to develop first, than for any other streams; and it must be understood that the figures are subject to revision dependent upon modifications of original plans to meet the conditions that develop upon more elaborate investigation.

[3] Preparations are to be made for storage of 120,000,000,000 gallons of water on the Esopus, but a part of this capacity is intended to accommodate supplies drawn from other sources than Esopus creek itself.



CATSKILL WATERSHEDS AND AQUEDUCT

(By courtesy of the

The evident certainty that present supplies from the Croton and Long Island will be very inadequate long before the Catskill system can be completed has influenced the adoption of plans contemplating the construction of certain parts in advance of the rest. To begin with, only the Esopus watershed is to be developed by the construction of the great Ashokan dam at Olive Bridge making the reservoir of full capacity. At the same time that portion of the aqueduct between the Ashokan dam and the present Croton reservoir is to be completed in advance of other parts so as to make it possible to turn additional supplies into the Croton system, the capacity of the present Croton aqueducts being somewhat in excess of the Croton storage in dry years. It is furthermore desirable that increased storage capacity should be secured much nearer to New York city, and with that end in view Kensico reservoir is to be greatly enlarged. It is estimated that this may be made to hold 50 days' supply of 500,000,000 gallons daily.

The development of the Catskill system is being carried on by the Board of Water Supply, which was appointed by Mayor McClellan, as provided in chapter 724, of the laws of 1905. The present board consists of John A. Bensel, *president*, Charles N. Chadwick and Charles A. Shaw. The Engineering Bureau of the Board is in charge of J. Waldo Smith, as chief engineer, Merritt H. Smith, as deputy chief engineer and Thaddeus Merriman, assistant to chief engineer.

Influenced doubtless in large part by the unity of certain portions of the project, either because their essential engineering features are distinct, or because their construction is more urgent, or in order to facilitate the work of supervision of so great an undertaking, the following departments have been created:

1 Headquarters department (executive). In charge of general designs, plans of construction and preparation of contracts. Alfred D. Flinn, department engineer.

2 Reservoir department. In charge of development of the Catskill watershed and the construction of the various dams and reservoirs. Carlton E. Davis, department engineer.

3 Northern aqueduct department. In charge of the construction of full capacity aqueduct from the Ashokan dam (60 miles) to Hunters brook in the Croton system. Robert Ridgway, department engineer.

4 Southern aqueduct department. In charge of the construction of full capacity aqueduct from Hunters brook in the Croton system

to Hill View reservoir on the northern limits of New York city and of the storage reservoirs and filtration work. Merritt H. Smith, and more recently F. E. Winsor, department engineer.

5 Long Island department. In charge of the development of the underground water supply of Long Island. A plan looking toward this end has been prepared and approved by the city authorities and is now being reviewed by the State Water Supply Commission.

6 City aqueduct division. In charge of the delivery of water from Hill View reservoir throughout Greater New York. Originally in charge of W. W. Brush, now under Walter E. Spear, as department engineer.

Departments are further divided into "divisions" each in charge of a division engineer and a full corps of assistants. The subdivisions of these larger units, although primarily based upon convenience and efficiency of engineering supervision, coincides rather closely with the larger geologic problems included in this bulletin.

Generalities of construction

The chief types of structure projected include (1) masonry dams, (2) earth dikes with core walls, (3) "cut and cover" aqueduct through country of about the elevation of hydraulic grade, (4) tunnels through mountains or ridges that are too high, and (5) pressure tunnels under valleys or gorges that are too low.

Some of these are of record proportions. For some of the details and figures *see* the different special problems in part 2.

All items complete as planned involve a total of:

10 dams
10 impounding, storage and distributing reservoirs
4.5 miles of dikes
54.5 miles of "cut and cover" aqueduct
13.9 miles of tunnel at grade
17.3 miles of pressure tunnel below grade
34 shafts of aggregate depth of 14,723 feet.
6.3 miles of steel pipes making
92.5 miles of aqueduct complete to Hill View equalizing reservoir
1 filtration works
18.0 miles of delivery tunnel in New York city to the terminal shafts in Brooklyn
16.3 miles of delivery pipe lines

Allowing for contingencies and costs for engineering supervision the system is estimated to cost $176,000,000 and many years will be required for its completion. The present plans, however, contemplate only the immediate development of the Esopus watershed, the storage reservoirs near the city and the main aqueduct to the various points of delivery within the city limits. It is expected that part of this additional supply of water will be available by the year 1913, or early in 1914.

CHAPTER II

PROBLEMS ENCOUNTERED IN THE PROJECT

When the Ashokan reservoir is filled the surface of the stored waters will stand 590 feet above the sea. Hill View reservoir on the northern borders of New York city will have an elevation of 295 feet. The distance between these two points is nearly 75 miles in direct line. The contour of the country and other exigencies of construction will increase this to approximately 92 miles. A main distributary conduit in New York city will add 18 miles more.

The destination of the water therefore before distribution begins is 300 feet lower than its starting point. This is sufficient head to permit gravitational flow and a self-delivering system. If the hydraulic gradient can be maintained it would evidently constitute a decided advantage. The plans have therefore from the beginning contemplated such construction. It means then that a flowing grade must be maintained in all tunnels or channels or tubes and that when a depression has to be crossed the pressure must be maintained in some sort of a conduit so that the water may rise again to a suitable level on the other side.

The difficulties of accomplishing this in a work of such magnitude are not at first apparent. The full significance of the undertaking can be realized only after a study of the country through which the aqueduct must be carried. It then resolves itself into a series of problems, each one having its own characteristics and peculiar difficulties and methods of solution and each requiring a thorough understanding of the topographic features of the vicinity and a working knowledge of geologic conditions.

General questions

It is sufficient at this point to call attention to the facts of the topographic map and point out only the most general physiographic features that may at once be seen to materially modify the simplicity of the line.

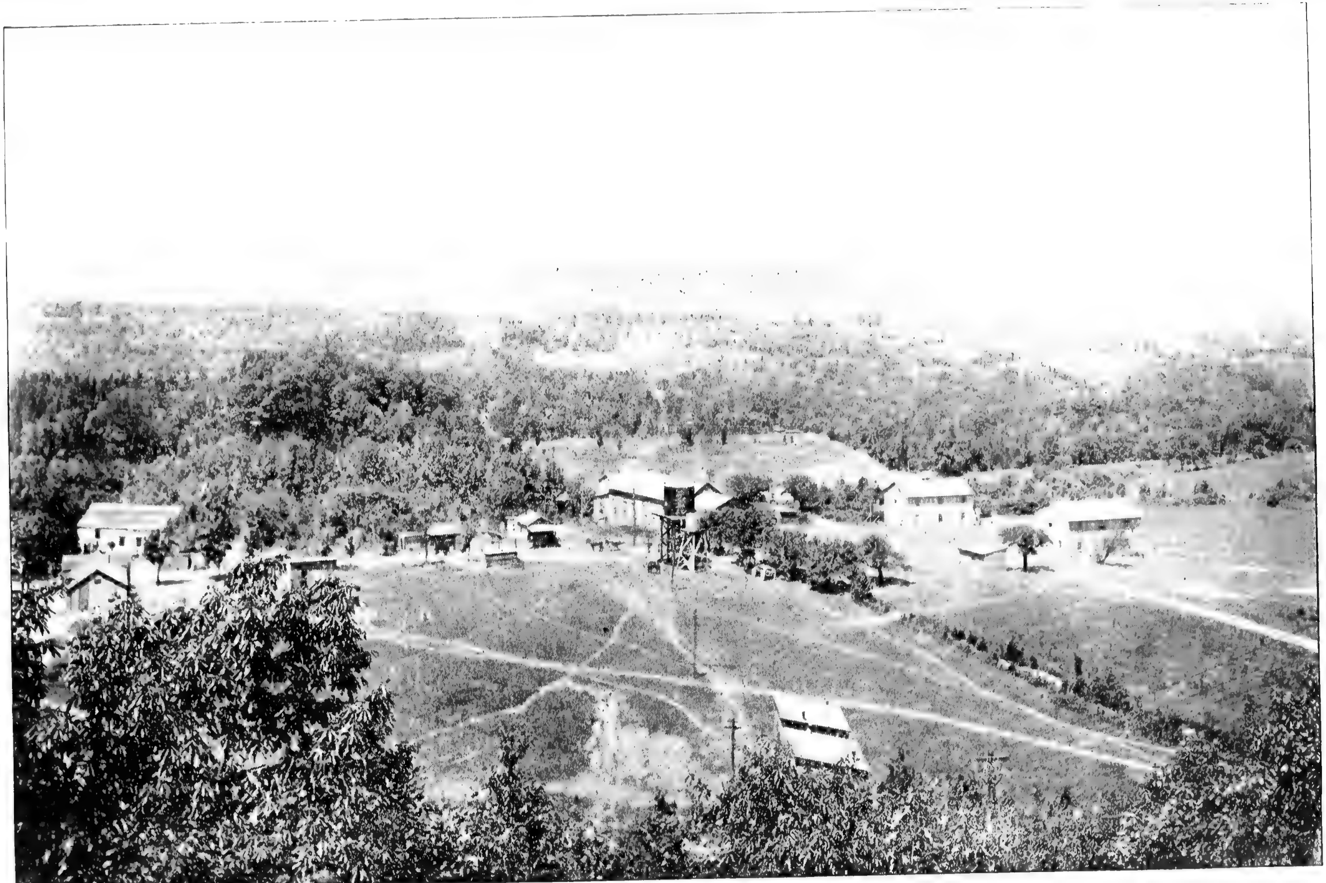
For example, one has scarcely left the great reservoir, with water flowing at 580–90 feet above tide, before the broad Rondout valley is reached, with a width of 4½ miles nowhere at great enough elevation to carry the aqueduct at grade. If it is to be crossed at all, and it must be crossed to reach New York city, some

special means must be devised. If a trestle be proposed, one finds that it would have to be 4½ miles long (24,000 feet), and in some places 300 feet high, and at all points large enough and strong enough to carry a stream of water capable of delivering 500,000,000 gallons daily — a stream that if confined in a tube of cylindrical form would have a diameter of about 15 feet.

A steel tube might be laid to carry the water across and deliver it again at flowing grade, but here one is met with the fact that it would require a tube of unprecedented size and strength and if divided into a number of smaller ones the cost would be greater than that of a tunnel in solid rock.

The other alternative is to make a tunnel deep enough in bed rock to lie beneath surface weaknesses and superficial gorges and in it carry the water under pressure to the opposite side of the valley. This is the plan that seems best suited to the magnitude of the undertaking and would seem to promise most permanent construction. But no sooner is this conclusion reached than it is realized that there are now several hitherto unregarded features that assume immediate and controlling importance. Some of these, for example, are (1) the possibility of old stream gorges that are buried beneath the soil, (2) the position of these old channels and their depth, (3) the kinds of rock in the valley, (4) their character for construction and permanence, (5) the possible interference of underground water circulation, (6) the possible excessive losses of water through porosity of strata, (7) the proper depth at which the tunnel should be placed, (8) the kinds of strata, and their respective amounts that will be cut at the chosen depth, (9) the position and character of the weak spots with an estimate of their influence on the practicability of the tunnel proposition. Then after these have all been considered the whole situation must be interpreted and translated into such practical engineering terms as whether or not the tunnel method is practicable, and at what point and at what depth it should cross the valley, and at what points still further exploration would add data of value in correcting estimates and governing construction and controlling contracts.

This is a general view of one case, the first one of any large proportions in following down the aqueduct. There are many others. In nearly all of them the importance of geologic questions is prominent. Many of them, of course, are of the simplest sort, but, on the other hand, some are among the most obscure and evasive problems of the science. And they do not become any



General view of the Rondout valley looking north along the aqueduct line from the margin of the Shawangunk range toward the Catskills. (Photograph by New York City Board of Water Supply)

easier simply to know that they must ultimately be stated in terms precise enough for the use of engineers, and to know furthermore that the real facts are to be laid bare when construction begins and as it progresses. But from another viewpoint it may be regarded as an exceptionally fine opportunity to study applied geology in its best form and to see the intimate interrelationship between an engineering enterprise of great public utility and a commonly considered more or less obscure science. The services of geology have been seldom so consistently employed in earlier undertakings of similar character. It is to be hoped that the accompanying illustrations of the practical application of geologic knowledge and facts to engineering plans and practice may add to the appreciation of the commonness and variety of such service in many everyday affairs. Furthermore, this unique enterprise, the like of which for magnitude and complexity has never before been attempted, has given to those whose good fortune has brought them into working relations with its problems, the opportunity of a generation in their chosen field.[1] The success stages from isolated observations, inference, hypothesis, theory, conclusions, and fully proven facts are all represented. The steps more or less fully coincide with the degree of confidence observable in the tone of advisory reports to the engineers in charge — representing suggestions, recommendations, or specific advice.

It is one of the cherished wishes of the writer of this bulletin that some of these problems may be presented in such manner as to serve a distinct educational purpose. For this reason in part, deeming it even of greater importance than the mere enumeration of newly discovered facts, the writer has chosen to treat the subject from the standpoint of an instructor illustrating the development of working conclusions. It is certain that not all readers have the same degree of preparation or acquaintance with the subject-matter, and it may therefore be useful to include many things that some may well pass by. No excuse is offered except that such method of treatment, in behalf of the general intelligent public that it is hoped to reach, seems to the author to be advisable.

[1] W. O. Crosby of the Massachusetts Institute of Technology, James F. Kemp and Charles P. Berkey of Columbia University have constituted the staff of consulting geologists throughout most of the exploratory work.

Other problems

The foregoing observations apply likewise to the other larger problems of the aqueduct line. A list of the larger ones requiring extensive exploration and illustrating geologic application in their solution are given below:

1 Location of the Ashokan dam
2 Sources of material for construction
3 Crossing the Rondout valley
4 The Wallkill valley
5 Moodna buried valley
6 Pagenstechers gorge and Storm King mountain
7 The Hudson river crossing problem
8 The Storm King-Break Neck cross section
9 Foundry brook
10 Sprout brook notch
11 Peekskill creek valley
12 Croton lake pressure tunnel
13 Bryn Mawr siphon
14 The new Kensico dam
15 Kensico quarries
16 New York city delivery tunnel

In addition to these there are several questions of general bearing in which the chief lines of argument and the chief basis of conclusion are essentially geologic. Although little wholly new data is yet available on these particular questions from any direct work of the aqueduct, yet it will add materially to an appreciation of the far-reaching influence of established geologic data and geologic reasoning to enumerate some of them:

17 Continental subsidence and elevation
18 Crustal warping
19 Postglacial and present faulting
20 Underground water circulation
21 Relative resistance of the different formations to corrosion by aqueduct waters
22 Structural materials

Each of these problems or questions or topics is discussed separately, so far as practicable. By adopting this plan, of course there is a tendency to repetition but this to a certain extent is unavoidable. Some of it is overcome by suitable references to preceding

discussions. Where such cross reference is too cumbersome, the items are repeated in preference to leaving the case obscure. Thus it is hoped to make each case a unit, and the whole series useful and understandable.

Gathering data

In the accumulation of data all the members of the engineering corps[1] as well as the men acting only in a consulting capacity have taken part. Necessarily the bulk of the exact data has been gathered by the men all the time on the ground and whose duty it was to superintend explorations. The care and intelligence with which this has been done is notable. A considerable proportion of the labor of manipulating the accumulated data and interpreting it so as to reach an explanation of conditions and formulate conclusions has been assumed by the consulting men.

Too much credit can not be given to the heads of departments and divisions for the open-handed way in which all needed facts were held available at all times for comparison and guidance toward sound conclusions. The information upon which investigations have been initiated have been chiefly the following:

1 The geologic maps and reports of the New York State Survey
2 United States topographic maps
3 Geologic folio no. 83, New York city folio
4 Earlier engineering records and reports
5 Reports of special commissions on water supply

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[1] In this work, no group of men have had so direct responsibility as the division engineers. The success with which so many complicated explorations were carried out is chiefly due to their constant care and foresight and perseverance and the able assistance of their staff. Those who have had especially important divisions for the geological problems involved are given due credit in the discussions of part 2, of this bulletin. It is easy, however, to neglect sufficiently full acknowledgment of their services in gathering and formulating data of this kind. Among those having charge of the most important exploratory work the following names should appear:

James F. Sanborn, for sometime assigned to geologic work on the Northern aqueduct.

William E. Swift, in charge of the Hudson river explorations.

William W. Brush, in charge of the early New York city explorations.

Lazarus White, in charge of the Rondout valley explorations.

Lawrence C. Brink, in charge of the Wallkill division explorations.

J. S. Langthorn, in charge of the exploratory work at the Ashokan Reservoir.

Wilson Fitch Smith, in charge of work at Kensico dam, and

A. A. Sproul, in charge of the Peekskill creek and Sprout brook explorations.

Some of these are printed reports and records not directly concerned with this enterprise, but whose information has been found useful in this field. This is especially true of the first four sources enumerated, 1, 2, 3, 4. The last is a specific study with direct reference to this project.

Investigations were begun from the above vantage point. The methods employed and the explorations conducted constituting the further sources of information and furnishing the complete data upon which all conclusions have been based include the following:

6 Detailed topographic studies of the engineers of the Board of Water Supply

7 Geologic field work making observations in detail of all geologic factors that seem to bear on the problem in hand

8 Wash borings for depth to bed rock

9 Chop drill holes through stony ground to bed rock

10 Shot drill holes in bed rock

11 Diamond drill holes

12 Test pits and trenches for detail of drift structure

13 Test tunnels in rock for working quality

14 Deflection tests for holes that have swerved aside

15 Pumping tests for underground water supply

16 Pressure tests for rock porosity

17 Microscopic examinations of rock types

18 Laboratory tests of quality and behavior of materials.

The mass of data accumulated from all these sources is surprising. For example, there are upward of 200 wash borings on the different proposed Hudson river crossing lines alone; there are 69 drill borings and 177 wash borings on the site of Kensico dam; there are 69 shot and diamond drill holes on the Rondout siphon line aggregating 10,234 feet of rock core; there are 65 drill holes of various sorts on the Moodna creek siphon aggregating in total penetration of drift over 10,000 feet; there are 106 borings, besides several pits and trenches at Ashokan dam location. At every point explorations suitable to the particular problems in hand were conducted. The whole mass of data is conveniently recorded, much of it is tabulated, some of it is represented graphically, samples of nearly all of the material are available for examination,[1] and all

[1] The cores of all drillings and suitable samples of all borings in drift have been saved and properly labeled and are to be permanently housed at some convenient point on the aqueduct line when completed. At present they are cared for at the different division offices.

have been made use of in coming to a consistent understanding of the conditions.

But the amount of accumulated data is no more remarkable than the difficulties that have been encountered in obtaining it. For example, in the Moodna valley it has taken three to four months' time to put down a single hole to bed rock — the average time consumed for each of the 15 holes exploring the deepest portion of the valley was about 60 days. The chief trouble is caused by heavy bouldery till. In one case a boulder was penetrated for 35 feet, lying a hundred feet above bed rock.

The extreme of such difficulty is, of course, encountered in the Hudson river itself, where the drill has to contend with: (1) the rise and fall of the tides, (2) the river currents, (3) a maximum of 90 feet of water, approximately 700 feet of silt, gravel, till, boulders, etc., filling the old preglacial gorge. The heavy steamboat and towing traffic has been a serious element in the problem. Probably never anywhere have drillmen had to face so nearly insurmountable obstacles. In two years only two holes reached below a depth of 600 feet below sea level. A third, now in progress, has penetrated a depth of 768 feet without entering rock.

CHAPTER III

RELATIVE VALUES OF DIFFERENT SOURCES OF INFORMATION AND STAGES OF DEVELOPMENT

In the earlier stages of work topographic features were of most concern, and they largely controlled the selection of reservoir sites and possible lines for the aqueduct to follow. It was, however, at once recognized that tunnels would be unavoidable and studies as to the types of rock formations to be encountered were begun It was also early appreciated that the soil or drift cover is very unevenly distributed over the rock surface and that, especially in the chief valleys requiring pressure tunnels, it would be necessary to determine the profile of the rock floor. At this point wash borings were begun. But the natural limitations of the wash rig[1] for penetrating drift of all kinds left the information still too indefinite. The wash rig can not penetrate hard rock. It can not wash up anything but the finer matter, and a boulder of very moderate size is almost as effectual a barrier as true rock ledge. By a combination of washing and chopping or by the use of an explosive to break or dislodge an obstruction some progress in unfavorable material may be made, but the wash rig alone, in a drift-covered region, gives only negative results. It is certain, for example, that bed rock lies at least as deep as the wash rig has penetrated, but it is not certain that it is bed rock instead of some other obstruction. Except in areas of special drift conditions,[2] therefore, the wash rig was insufficient. To rely upon the process at random was clearly impossible, and to determine whether or not the results of a particular locality

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[1] A "wash rig" is a device composed essentially of two iron pipes, one within the other, and so mounted that the inner one can be worked up and down in sort of a churning fashion while water under considerable pressure is forced through it to the bottom and out again by the larger pipe to the surface, carrying up with the current the displaced sand and clay. As progress is made with the inner pipe the outer one is from time to time driven down and the process renewed and repeated till the hole is finished.

[2] One of the most notable areas of special drift conditions is represented in the Wallkill valley [*see* discussion in pt 2] where there were developed large deposits of modified drift, stratified gravel, sand and clays, lying immediately upon the bed rock floor. In this the wash bore process was eminently satisfactory, and the rapid progress made by it together with its economy made this an especially attractive method of exploration.

could be relied upon became involved at once with an interpretation of local glacial phenomena, especially an interpretation of the character of the local drift. In order to see the limited application of this method one needs only to point out that the majority of drift deposits in this region are stony or even bouldery, forming thick coverings in the valleys, and to call attention to the experience at two or three points. For example, at Moodna creek, the preliminary wash borings were obstructed and bed rock reported at 5 to 15 feet below the surface where afterward, by other means, it was proven to lie more than 300 feet down. Or again, in the preliminary wash borings in the Hudson, the rigs were stopped and rock bottom provisionally reported at from 25 to 200 feet below sea level, but later explorations have proven at the same point that rock bottom is more than 700 feet down.

Therefore, to the "wash rig" was added the "chop drill" and the "oil-well rig" and to these, or to modifications of them,[1] the success in reaching bed rock has been due.

From independent field studies of a more strictly geologic nature it became clear that many of the valleys, where pressure tunnels were proposed, are of comparatively complex geologic structure and exhibit considerable variety of rock quality and condition. This then introduced and necessitated still more elaborate lines of exploration. It was not enough to know the profile of rock floor alone, it became of equal importance to penetrate the rock and obtain samples of it. So the shot drill[2] and the diamond drill[3] were employed and the drill cores preserved for identification and reference.

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[1] The essential features of the machines in most instances are, a high tower or support, a heavy chisel-shaped plunger that can be raised by a rope and dropped repeatedly in the hole, destroying or displacing obstructions, and which can be followed by a casing driven down as progress is made — a combination of washing, chopping and driving.

[2] The shot drill, or calyx drill, is essentially a machine devised to rotate a steel tube which is so adjusted and manipulated that a supply of small chilled shot can be kept continually under the lower end as it bores into the rock. The cutting is done by the shot immediately under the edge of the tube. A core remains in the tube and may be recovered. Its best position is vertical.

[3] The diamond drill consists essentially of a bit or crown set with black diamonds (bort) in such manner that when the bit is attached to a rotating tube a circular groove is cut into the rock. By proper attachment to jointed tubes and driving gear a hole may thus be bored at any angle and to great depth and a core recovered.

These preserved cores, now aggregating many thousands of feet have been of great service in determining the precise limits of formations and consequently the geologic structure or cross section, by which detailed estimates may be guided.

Even these occasionally appeared to give insufficient data. The peculiar behavior of certain holes, as, for example, one or more at Foundry brook,[1] led to the suspicion that the drill had swerved from its course, following a particularly soft seam or zone, and that the results secured by it without large corrections, were wholly misleading. Tests proved that there had been a deflection.

At this and many other places it later became very desirable to form some quantitative as well as qualitative opinion of the conditions existing in the underlying strata. The percentage of core saved, the rate of progress of the drill, the behavior of the drill, the condition of the core recovered, the loss of water in the hole — all these of course were considered.

For more definite evidence as to porosity and perviousness, a series of carefully planned pressure tests[2] were made. By shutting off connection with the walls of the hole above a certain stratum and forcing water in under pressure, it was possible to demonstrate that certain strata or certain portions were practically impervious in their natural bed, while others were much less so, and to get an idea of their relative efficiency as water carriers. For the pressure tunnels, especially, this test is a very suggestive line of investigation.

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[1] At Foundry brook [*see* discussion of this problem in pt 2], the remarkable condition apparently shown was a reasonably substantial ledge of granitic gneiss, 50 feet, followed below by 200 feet of apparently soft sand and reported as such. No core could be recovered. So extensive a zone or bed or layer or mass is hardly conceivable considering the crystalline silicious character of the rock. It probably represents a steeply dipping crush zone along fault movement where the increased underground circulation has been unusually effective in producing decay. After entering this zone the drill swerved from its initial course and kept within the soft seam.

[2] The pressure test is made by means of a force pump, fitted with a gage on which the pressure is recorded, connected by a pipe to the portion of the hole to be tested, and so adjusted to a device for blockading or damming the hole that the water pressure is confined to those portions of the walls of the hole below the dam, or between two dams if an upper and lower one are used. In this way any portion of a hole, or stratum or several beds together may be tested and the amount of water absorbed per unit of time per unit of pressure determined. This is, of course, directly related to the porosity of the rock and is approximately inversely proportional to its presumed value as an aqueduct carrier.

Where the strata are especially porous and where underground or permanent ground water supplies are very extensive and where at the same time the largest or deepest pressure tunnels are projected some uneasiness has been entertained as to the extent of interference from inflowing water during construction. An attempt to form some idea of the ease of such underground circulation has been made by a systematic pumping of one or two critical holes. The results leave many factors still too obscure to draw definite conclusions. The test will be taken up again in the discussion of the Rondout siphon in part 2.

Laboratory tests and experiments on materials complete the list of lines of investigation with which this bulletin is concerned. Although from the nature of the case these are elaborate and unusually complete, the more important lines are not at all new. All the methods of petrographic, chemical, and physical manipulation that seem to promise practical results of value to the success of the undertaking are followed and the data are organized and interpreted and conclusions are formulated with as great definiteness for practical bearing as other lines of investigation.

CHAPTER IV

GENERAL GEOLOGY OF THE REGION

It will save much repetition and it is believed will altogether serve a useful purpose in maintaining unity of treatment to give an outline of the geologic features of the region in advance of the discussion of special problems. It is intended only for those not sufficiently familiar with the general geology to follow subsequent matters.

The region includes some of the most complicated and obscure sections of New York geology. It is simple in almost no one of the larger branches of the subject. In physiography there is the long and involved history and the results of long continued erosion of a variable series of formations in different stages of modification as to structure and metamorphism and attitude, modified still further by subsidences and elevations, depositions and denudations, peneplanations and rejuvenations, glaciation and recent erosion — all together introducing as much complexity as can well be found in a single area.

In stratigraphy the whole range of the eastern New York geologic column is represented from the oldest known formation up to and including the Middle Devonic — a succession of at least 25 distinct formations which may for convenience be treated in groups that have had similar history. Each of these formations has a constant enough character to map and regard as a physical unit. Even this classification ignores the great range of petrographic variability shown in such formations as the Highlands or Fordham gneisses. All but two or three of these formations will be cut by the tunnels of the aqueduct.

In petrography the range is even greater — so great, in fact, that only an enumeration of the variations will be attempted. They include clastics, metamorphics and igneous types; stratified and unassorted, coarse and fine, detrital and organic, marine and fresh water, homogeneous and heterogeneous, argillaceous, calcareous and silicious sediments, unmodified and thoroughly recrystallized strata; acid and basic and intermediate intrusions; massive and foliated crystallines — of many varieties or variations in each group.

In tectonic geology an equal complexity prevails. There are regular stratifications, cross-beddings, disconformities, overlaps and unconformities; interbeddings, lenses and wedges; flat, warped, tilted

and crumpled strata; monoclinal and isoclinal, open and closed, anticlinal and synclinal, symmetrical and overturned, horizontal and pitching folds; joints, crevices, caves, crush zones, shear zones, and contacts; normal, thrust, dip, strike, large and small faults; veins, segregations, inclusions, dikes, sills, bosses and bysmaliths.

With such variety of natural conditions it is not surprising that the problems of the aqueduct are also of great variety. No two have in all respects the same factors in control and no two can be explored and interpreted upon exactly the same lines.

1 Geographic features or districts. (Physical geography[1])

It will be convenient at this point to think of the surface topography by districts — not wholly distinct from each other, but still with essential differences of origin and form. From south to north they are: (*a*) New York-Westchester county district. The area of crystalline sediments. South of the Highlands. (*b*) Highlands of the Hudson (Putnam county). (*c*) Wallkill-Newburgh district. From the Highlands to the Shawangunk range. (*d*) Shawangunk range and Rondout valley. (*e*) Southern Catskills.

All have been sculptured by the same forces and with similar vicissitudes, but the difference of history and structure and condition, already established when the physiographic forces began on the work now seen, have caused the variety of surface features indicated in the divisions made above. The more noticeable characteristics of these five districts are here given.

a **New York-Westchester district.** The area south of the Highlands proper is characterized by a comparatively regular succession of nearly parallel ridges separated by valleys of nearly equal extent (½ to 5 miles wide), making a surface of gently fluted aspect and of moderate relief (0–500 feet) sloping endwise toward the Hudson and the sea. The controlling factors in producing this topography are involved in a series of folded, foliated, crystalline sediments, of differing resistance to destructive agencies.

b **The Highland region** is one of rugged features, with a range of elevation of 0–1600 feet A. T., forming mountain masses and ridges separated by very narrow valleys all having a general northeast and southwest trend across which the Hudson cuts its way in a narrow, angular gorge, forming the most constricted and crooked portion of its lower course. The bed rock is all crystalline,

[1] The physiographic history of a region is not understandable without a comprehensive knowledge of its geologic features and structures and history. It is therefore treated in a later paragraph.

Plate 3

View looking west from Sky Top in the Shawangunk range with Mohonk lake in the foreground and the Rondout valley in the distance with the Catskills in the background. (Photograph by the Board of Water Supply)

of massive and foliated types, metamorphosed sediments in part with large masses of igneous intrusions and bosses.

c **The Wallkill-Newburgh district** lying immediately north of the Highlands and extending to the Shawangunk range is a region of gently rolling contour. Most of the area along the proposed lines lies between 200 and 500 feet above the sea. There are only occasional rugged hills or short ridges, such as Snake hill and Skunnemunk. The valleys are broad and smooth and the divides are simply broad, hilly uplands. Bed rock is chiefly Hudson River slates with occasional belts of Wappinger limestone. The larger features, the trend of divides and valleys, are northeast and southwest, although this regularity is not so marked as in the preceding two districts. But the chief streams flow either northeast or southwest to the Hudson along these general lines.

d **The Shawangunk range and Rondout valley** form a transitional unit from the complicated structural and tectonic conditions of the southerly districts to the uniform and almost undisturbed strata of the Catskills. Its southeasterly half is a mountain ridge partaking of extensive faulting and folding and represented by the Hudson River slates overlain unconformably by the thick and very resistant Shawangunk conglomerate forming high eastward-facing cliffs. Toward the northwest these disturbances diminish, the strata gradually pass deeper beneath a great succession of shales, limestones, and sandstones of the Helderbergian series, and a broad valley is eroded in the softer portions. It is limited on the northwest by the prominent and very persistent escarpment bordering the Hamilton series and forming the outer margin of the Catskill mountains.

e **The Catskill area** is of simple structure. The strata are well bedded and lie almost flat with a gentle dip northwest. The surface features form a series of irregularly distributed escarpments, hills, valleys, cliffs, gorges and mountains, rising rapidly toward the west, with moderate to strong relief and reaching elevations of 2500 feet. The failure of the northeast-southwest trend of feature that is so common in all of the other districts is a marked difference. It is directly due to the flatness of the strata.

2 Stratigraphy

There are no strata of prominence in association with the main aqueduct younger than Devonic age except the glacial drift. Immediately adjacent areas, however, some of which are covered by the accompanying maps, and Long Island have later formations ex-

tensively developed. Such are the Triassic rocks of the New Jersey side of the Hudson below the Highlands, and the Cretaceous and Tertiary strata of the Atlantic margin on Long Island and Staten Island. The development of underground water supply on Long Island is especially concerned with these later formations, and with the modified drift deposits of the continental margin.

The whole series of formations are more commonly considered in groups that exhibit certain age or physical unity and that are for the most part characteristic of certain regional belts and that coincide somewhat roughly with the physiographic divisions already noted. There is in the following description and tabulation no direct attempt to unduly emphasize this relation or to belittle the divisions recognized in the commonly adopted geologic column. It is, however, for the purpose in hand, more convenient and useful to keep clear the physical groupings, because largely these groups, instead of the more arbitrary subdivisions of age, are the units used in considering structural and applied problems.

a **Quaternary deposits.** (1) *Glacial drift.* A loose mantle of soil and mixed rock matter covers the bed rock throughout the whole region except (*a*) here and there where the rock sticks up through (outcrops), and (*b*) at the most southerly margin along the coast where the glaciers seem not to have reached.

Origin. This mantle is usually very different in lithologic character from the underlying rock floor. There is almost always an abrupt break between the rock floor and the overlying material. The rock floor is grooved, smoothed, and scratched as if by the moving of rock or gravel over it. The larger boulders are usually of types of rock identical with ledges lying northward at greater or less distance. Materials of exceedingly great variety both in size and condition and lithologic character are often all piled together in the most hopelessly heterogeneous manner. These are now commonly regarded as conclusive evidence of glacial origin. There is no need of making the discussion exhaustive. It is almost universally called the "*drift.*"

Thickness. The thickness of the drift varies from almost 0 to approximately 500 feet. It is generally thickest in the valleys where it has simply filled many of the original depressions and obliterated much of the ruggedness of surface, the gorges and ravines and canyons of the preglacial time.

Sources. It appears from an examination of the grooves and striae on bed rock, and the relationship of the different types of drift to each other, and from a comparison of the types of boulders

with the ledges that may be regarded as their source, that the general ice movement was from north to south swerving along the southerly extension to east of south. Therefore it is not unusual to find abundant boulders of Palisade trap stranded in New York city or on Long Island, or boulders of the Cortlandt series, or of the gneisses of the Highlands, or, in occasional instances, of sand stones from the Catskills, or the limestones from the Helderbergs or perhaps in rarer cases even rocks from greater distance, as the Adirondack mountains.

Kinds of drift. There are in the region two fundamentally different types of drift as to method of deposition. They are (*a*) unassorted drift (till or hardpan), and (*b*) modified drift (stratified or partially assorted gravels, sands, clay, etc.). The former (*a*) represents deposition directly from the ice sheet at its margin (terminal or marginal moraines) or beneath ("ground moraine") without enough water action to rework and assort the material. It therefore contains boulders, pebbles, sand and clay of a heterogeneous mixture of the most complex sort both as to size and character. In such deposits there is almost always sufficient intermixture of clay and rock flour of the finest sort to make a very compact and dense mass that is usually quite impervious to water. Such deposits are distributed rather unevenly over the surface and where this unevenness leaves hollows or basins, or obstructs the outlets of other depressions, they may hold water and form small lakes or ponds or swamps. This is almost universally the origin of the many thousands of lakes of the northern lake region. It is evident that material of this character, a type that commonly serves the purpose of a natural dam or reservoir, would be especially important and useful at certain places on the Catskill system. As a matter of fact, so far as geologic features are concerned, it is the chief factor in choice of location for the Ashokan dam [*see* discussion pt 2] and is a controlling factor in the plans for the erection of the miles of dikes at less critical margins of the reservoirs. Till is an extensively developed type but frequently passes abruptly either laterally or vertically into assorted materials of very different physical character.

(*b*) All materials associated in origin with the glacial occupation that have been materially modified especially in the direction of an assorting of material are referred to as "modified drift" deposits. They include (1) deposits made by both water and ice together, (2) those formed by running water, (3) those laid down in stand-

ing water. Or again (1) those accumulated rapidly with very irregular supply of material at the margin of the ice-forming, hummocky or hill and kettle surface (kames, eskers), (2) those carried along valleys or general lines of drainage to a considerable distance beyond the ice margin aggrading the valley with the overload of gravels and sands (valley trains), (3) those washed out from the ice margin in more even distribution forming a gently sloping and thinning extramarginal fringe (outwash or apron plains), (4) those fine matters that are carried by glacial streams into the margins of more quiet waters, either a temporary or a permanent lake or a larger and slower stream or other body forming more perfectly assorted and more evenly stratified deposits (delta deposits), (5) those finer rock flours and clays that remain suspended longer and carry out much farther settling only in the very quiet waters of lakes or estuaries or temporary water bodies of this character forming the perfectly banded clays (glacial lacustrine clays).

It is evident then that modified drift has in the process of its accumulation suffered chiefly a separation of fine from the coarse particles and that in most cases the fine clay filling that makes the till dense and impervious to water, has been washed out and deposited by itself in the more inaccessible deeper waters. As a result most modified drift deposits are pervious and easy water conductors, but poor or questionable ground for dikes or dams or basins [*see* discussion of Ashokan dam, pt 2].

Some of them, the medium sands and gravels, furnish an excellent and already cleaned structural material for concrete or mortar, such as the Horton sand deposit, or coarser kinds may be crushed and sized before using as is done at Jones Point on the Hudson.

The finer silts and clays, usually overlain by assorted sands, are abundant along the Hudson, having been deposited there at a time when the water of this estuary stood 50 to 150 feet higher than now. Recent erosive activity of the river has cut the greater proportion of the original deposits away but at many places large quantities still remain above water level in the banks and still greater quantities extend beneath the river. These deposits are the support of the brick industry of southeastern New York. The till deposits are very difficult to penetrate in making borings because of the boulders, the wash rig being almost useless. Modified drift of the medium and finer sorts is easily and cheaply penetrated, and, if it lies on bed rock, such exploration gives reliable results.

Structure. But this is stating the actual conditions too simply. The glacial epoch was a complex one The continental ice sheet may

have advanced and retreated repeatedly, how many times in this region is not clear. With each time of advance and retreat, the work done by it partly destroyed, or disturbed or modified or covered the earlier ones in what appears now to be a most arbitrary way (in reality, of course, in a very consistent way for the conditions that then existed). So one frequently finds a till beneath a deposit of stratified drift, or modified drift beneath till, or a succession of a still greater number of changes in almost hopeless confusion. In New York city, for example, at Manhattanville cross valley, the exposed drift above street level includes (*a*) at the bottom, water-marked stony till and assorted gravels, (*b*) in the middle perfectly horizontal, stratified rock flour and the finest sand, (*c*) top, wholly unassorted bouldery till, covered by thin soil. It is evident that the most careful and accurate identification of the surface type without subsurface investigation would give, for such uses as are now being considered, thoroughly unreliable evidence as to the behavior of the whole body at this point. Therefore, a determination of the changes and quality forms an essential record. All of these types are to be found in the region, but the different grades of till and roughly modified material belonging to the kame type are more common inland.

On Long Island the development of marginal modified types is extensive and more or less obscured by the advance and retreat noted above. The larger divisions recognized in deposits are (*a*) an early accumulation of sands and gravels, strongly developed near the western end of the island, known as the "Jameco" gravel, (*b*) an interglacial (retreatal) deposit of blue clays known as the "Sankaty" beds, (*c*) a later series of deposits, sands, clays, gravels and till, belonging to the closing stages of the ice period corresponding to the surface deposits of the larger portion of the whole region (Tisbury and Wisconsin advances). Some of these sands and gravels are important water-bearing sources for the new Brooklyn additional supply.

The whole Long Island series according to Veatch[1] includes:

Wisconsin stage	Glacial two lines of terminal moraines with outwash plains	Harbor hill moraine Ronkonkoma moraine
Tisbury stage	Great deposit of outwash sand and gravel (depression) Gardiner interval with erosion (interglacial)	

[1] After PP 44, U. S. Geological Survey, p. 33.

Gay Head	Folding (glacial folding) Sankaty retreatal stage (interglacial) clay beds
Jameco	Glacial — Jameco gravels Postmannetto erosion (interglacial)
Mannetto stage	Glacial — old gravels

A radically different and in some respects a much simpler interpretation[1] of the Long Island deposits has been outlined by W. O. Crosby. The essential feature of his classification is the unity and simplicity of the glacial epoch. Only the moraines and associated sands and gravels of outwash origin during advance and retreat are regarded as glacial. All other deposits below and including the Sankaty clay beds he regards as preglacial.

The Jameco gravels are interpreted as Miocene in age.

Certain persistent yellow gravels overlying the Jameco are classified as Pliocene.

b **Tertiary and Cretaceous deposits.** (2) *Tertiary outliers.* Deposits of *Pliocene* age are littoral in type [PP 44 U. S. G. S. p. 28] and are not very well differentiated (Long Island, Staten Island). Probably equivalent to the *Bridgeton* beds of New Jersey.

Certain "fluffy" sands in thin beds are assigned by Mr Veatch to the *Miocene* (Long Island, Staten Island). Probably equivalent to the *Beacon hill* deposits of New Jersey. Crosby places the Jameco gravels in the Miocene together with the Kirkwood lignitic and pyritic clays and sands.

(3) *Upper Cretaceous* deposity[2] are extensively developed. They form the chief bed rock of Long Island.

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[1] The writer offers both of these outlines of the glacial and associated deposits in preference to either alone. Both Veatch and Crosby have given immensely more time to the study of these questions than any one else. It is hardly fitting for a newcomer in their field to reject either view. But because of the very great difference between the two interpretations one may be pardoned a preference. It is the writer's opinion that the simpler outline is the more tenable. It does not seem possible to establish a very complex series of stages in the glacial epoch as represented in the deposits of southeastern New York.

[2] Crosby's classification of the Cretaceous is as follows:

(*a*) Monmouth — slight development of marls. (Lower and middle marl series.)

(*b*) Matawan — (clay marl series) probably present on Long Island.

(*c*) Magothy — an extensive series of variegated and micaceous sands and clays. Heavy development on Long Island.

(*d*) Raritan — Plastic clay scales and the Lloyd sand.

(*a*) A lignitiferous sand with occasional clay beds forming the *uppermost* of the *Cretaceous* series is probably equivalent to the *marl* series of New Jersey. But it lacks the prominent greens and development characteristic of the region further south. Not clearly separable from the underlying formation or Matawan beds.

(*b*) The Matawan beds. Gray sands and clays.

(*c*) Raritan formation. Clays and sands, plastic clays, the *Lloyd sand,* an important water carrier lies about 200 feet below the top of the formation. Occasional leaf impressions.

All of these formations, except where disturbed locally by glacial ice, dip gently seaward. The sand beds of these strata are the chief sources of underground water being developed by the new system.

c **Jura-Trias formations.** (4) *Palisade diabase.* This is a thick intrusive sheet, or sill, of igneous rock of diabasic type. It is 700–1000 feet thick. It lies for the most part parallel to the bedding of the surrounding, inclosing, sedimentary rocks, and, rising gently eastward, forms a strong cliff continuously along the west bank of the Hudson for 40 miles. It varies from very fine to very coarse texture and is for the most part fresh, tough, durable, and is the source of large quantities of the most satisfactory quality of crushed stone now on the market for use in concrete.

(5) *Newark series.* This is a very great thickness of silicious sediments, chiefly reddish conglomerates, red and brown quartzose and feldspathic sandstones and shales. They dip gently westward and northwestward at 10–20 degrees, and are confined, in this region, to the west side of the Hudson south of the Highlands. The formation supplies " brownstone " for building purposes.

None of the Jura-Trias rocks, so far as known, will be cut by the aqueduct.

d **Devonic strata.** (6) *Catskill formation.* This formation[1] is of continental type, chiefly a conglomerate. A white conglomeratic sandstone forming the uppermost portion attains its greatest thickness on Slide mountain (350 feet). It is a " coarse grained, heavy bedded, moderately hard sandstone containing disseminated pebbles of quartz or light colored quartzite, and streaks of conglomerate."

A red conglomeratic sandstone constitutes the much thicker portion below (1375 feet). It is a " coarse, heavy bedded sandstone of dull brownish hue containing disseminated pebbles and conglomeratic streaks, differing from the overlying beds chiefly in color. In

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[1] Grabau, A. W. N. Y. State Mus. Bul. 92. Geology and Paleontology of the Schoharie Valley.

both series the pebbles and conglomeratic streaks are scattered and irregular, while the sands are often cross-bedded. Thin layers of red shale occur, and locally gray sandstones." The deposits probably represent flood plains, deltas, and alluvial fans accumulated mostly above sea level.

(7) *Oneonta sandstone* (Upper flagstone). "Thin and thick bedded sandstones from 20 to 200 feet thick with interbedded red shales up to 30 feet thick." Chiefly light gray to brown in color. Abundant cross-bedding, occasional dark shale, frequent flagstone beds. Capable of furnishing "bluestone" flags and more massive dimension stone. To be seen in the vicinity of West Shokan and westward.

(8) *Ithaca and Sherburne* (lower flagstone "bluestone"). "Thin bedded sandstone, with intercalated beds of dark shale. The sandstones are in masses from a few inches to 40 feet in thickness, greenish gray to light bluish gray or dark gray in color, and are extensively quarried as flagstones." There are occasional conglomeratic streaks. Occurs in large development in the vicinity of the Ashokan reservoir (500 feet). The heavier cross-bedded and coarser grained beds are capable of furnishing an unusually good quality of large dimension stone for heavy structural uses. The beds of this formation near Olive Bridge will in all probability furnish the greater proportion of stone of all kinds for the construction of the great Ashokan dam [*see* discussion of bluestone near Ashokan dam, pt 2]. The chief common fossil content is impressions of plant remains.

(9) *Hamilton and Marcellus shales.* "Dark gray to black or brown shales with thin arenaceous beds in the upper part." Forms the upper portion of the escarpment that follows the outer margin of the Catskill foothills bordering the westerly side of the middle Rondout and lower Esopus valleys. Occasionally beds are substantial enough for flagstone production (700 feet or more with the Marcellus.)

The chief index fossils are: Spirifer mucronatus, Athyris spiriferoides, Chonetes coronatus.

The Marcellus shale is not readily differentiated in the Esopus valley. Characteristically it is a thin bedded shale of no great thickness (180 feet in the Schoharie valley) lying between the Onondaga limestone and the Hamilton and obscured by talus from the escarpment (with the Hamilton 700 feet.)

Styliolina fissurella, Chonetes mucronatus, Strophalosia truncata, Liorhynchus mysia.

Plate 4

The Sherburne flags at Olive Bridge. (Photograph by Board of Water Supply)

The dividing lines between the different sandstones and shale formations, the Oneonta, Ithaca, Sherburne, Hamilton and Marcellus, can not be sharply drawn in the Esopus region. Together they form in a large way a rather satisfactory field unit. For specific purposes it is necessary to recognize that the lower portions are prevailingly shales with thin bedded sandstones while the upper portions are much more heavily bedded, the sandstones pre-

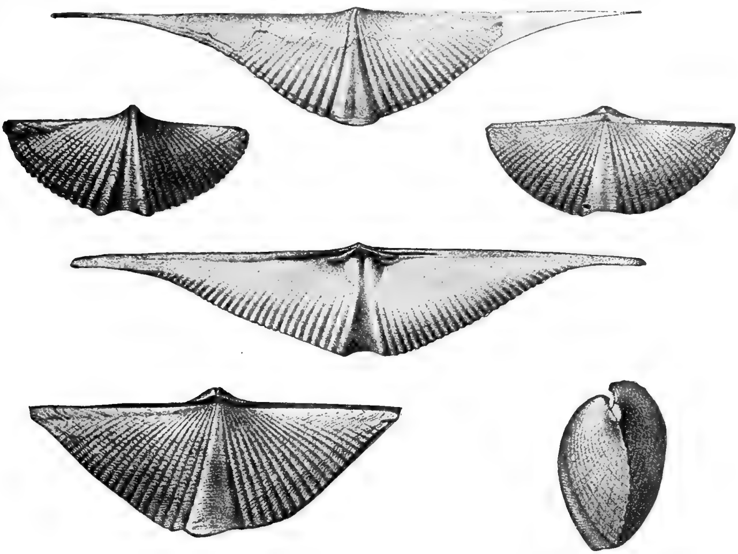


Fig. 2 Spirifer mucronatus (Conrad), a characteristic and abundant index fossil of the Hamilton shales of the Catskill margin

vailing. The five divisions may possibly be more satisfactorily made on paleontologic characters than on physical, but in most of the advisory reports on economic and practical problems involving this district the subdivisions can not be emphasized. The whole series is essentially conformable and is very little disturbed [*see* report on bluestone quarries, pt 2].

(10) *Onondaga limestone.* A bluish gray, massive, thick bedded cherty, somewhat crystalline limestone. It is strongly marked off from the Hamilton and Marcellus above, and, because of its greater resistance to erosion, usually forms a dip slope controlling stream adjustment and ultimately inducing the development of unsymmetrical valleys with gentle easterly slopes and clifflike westerly borders where the streams are sapping the overlying Marcellus and Hamilton shales. It is not sharply separable from the Esopus below but everywhere in this region graduates into it with increase of silicious

and argillaceous impurities. Estimating the formation from the drill cores that have penetrated it, and placing the lower limit as nearly as may be at the horizon of changes from predominant lime to predominant silicious content, the approximate thickness in this region is placed at 200 feet. The rock where exposed exhibits considerable joint development and these are considerably enlarged by the solvent action of percolating waters. This factor is considered of some importance in connection with the other limestones of the district in aqueduct construction and permanence. The Onondaga has been used as a building stone formerly sold as marble, some grades of which are good stone. On the line of the aqueduct it is confined to the Rondout and Esopus valleys. The chief fossils are: Atrypa reticularis, Zaphrentis prolifica, Leptostrophia perplana, Platyceras dumosum, Leptaena rhomboidalis, Dalmanites selenurus.

(11) *Esopus and Schoharie shales* (a slaty grit). The Schoharie as a distinct formation is not distinguishable in this region. The very thick and comparatively uniform, gritty, black, dense, almost structureless rock is a distinct unit. It is a silicious mud rock with very obscure sedimentation markings, but showing independent secondary cleavages induced by later dynamic factors, and, on long exposed surfaces always exhibiting chiplike fragments as the result of weathering. But it is not an easily destroyed rock. In so far as the bedding is obscure and the induced structure predominates, the rock is a slate; and in so far as it is distinctly gritty (sandy) instead of argillaceous it is a grit. The formation might therefore be more accurately designated as a slaty grit. The lack of plain bedding structure makes it impossible to estimate its thickness, since the foldings or other displacements can not be allowed for; but the accumulated data of drill holes in more advantageous position indicate an approximate thickness of 800 feet. The rock is considered exceptionally good ground for the tunnel.

A few fossils occur the most characteristic being Taonurus caudagalli. There are also in certain layers of limited extent, Leptocoelia acutiplicata and Atrypa spinosa.

(12) *Oriskany and Port Ewen transition* (silicious shaly limestone). There is no well defined and distinct separation here between the Oriskany and the underlying Port Ewen, but because of the importance and persistence of the formation in other and related areas the name is held. The equivalent of the Oriskany is in this district involved with a strongly developed transition zone which in physical features is intimately associated with the Port

Ewen as a single unit. If any distinct formation is to be recognized it would be on the basis of transitional faunal character, placing the fossiliferous upper 100 feet in the Oriskany transition and confining the name Port Ewen to the rather unfossiliferous and concretionary, shaly, argillaceous limestone of the lower 100 feet.

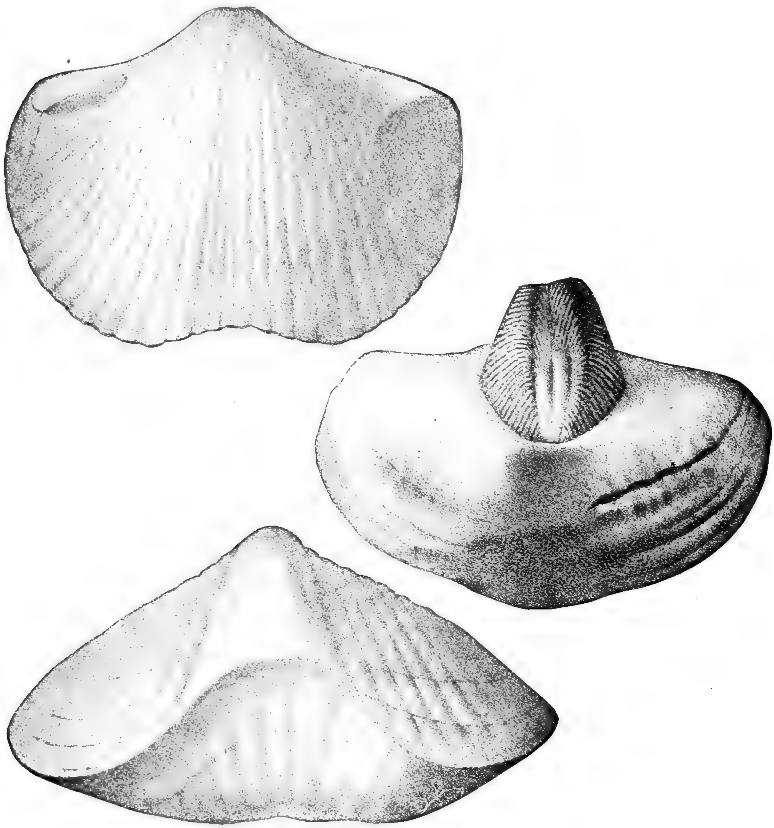


Fig. 3 *Spirifer arenosus* (Conrad), one of the characteristic index fossils of the Oriskany occurring in the Port Ewen-Oriskany transition

This transition rock is strongly bedded, argillaceous and silicious limestone, very quartzose in certain layers, but there are no exposures in this area that would be called sandstones. Fossils are abundant and show marked Oriskany peculiarities. Those of most characteristic relations are: *Hipparionyx proximus*, *Leptostrophia magnifica*, *Spirifer murchisoni*, *Spirifer arenosus*, *Platyceras nodosum*, *Strophostylus expansus*.

(13) *Port Ewen shaly limestone.* The beds below those noted in the preceding paragraph are essentially argillaceous, shaly limestones. They vary from rather massive to thin bedded, are dark grayish in color, and have a peculiar nodular or concretionary development along certain sedimentation lines. These spots have less resistance to weather than the surrounding rock and therefore develop rows of pits along the face of an outcrop. Their size, 6 to 18 inches or more across, together with their persistence makes an easily recognized physical feature. The few fossils that are found are not very characteristic. The following should be mentioned: Spirifer perlamellosus.

In the discussion and on the maps the Port Ewen and Oriskany are treated together as a single unit as the Oriskany-Port Ewen beds.

(14) *Becraft limestone.* Massive, heavy to thin bedded, light colored, semicrystalline to thoroughly crystalline limestone. More massive beds very pure, 94+% $CaCO_3$. Shaly beds resemble the New Scotland which they pass into at the base. The most characteristic features for field identification are (*a*) pink or light colored spots, (*b*) a more coarsely crystalline condition than any of the associated strata, (*c*) occasional large calcite cleavages to be seen wherever a fossil crinoid base Aspidocrinus scutelliformis is broken, (*d*) the very characteristic fossil Sieberella pseudogaleata, and (*e*) many crinoid stems.

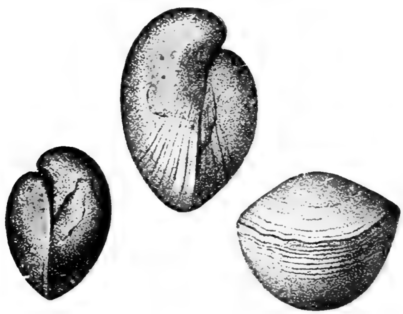


Fig. 4 Sieberella pseudogaleata Hall, the most characteristic index fossil of the Beacroft limestone of the Rondout region

The formation carries many fossils in addition to those given above, among which are Spirifer concinnus, Uncinulus campbellanus.

(15) *New Scotland shaly limestone.* Thin bedded, dark gray to reddish sandy and shaly limestones. The rock breaks out in slabs on weathering and develops red iron stains. It has especially abundant fossils, the most characteristic of which are: Orthothetes woolworthanus, Spirifer macropleura. Other common ones are: Leptaena rhomboidalis, Strophonella headleyana, Ripidomella oblata, Stropheodonta becki.

(16) *Coeymans limestone.* Heavy bedded, dark gray, argillaceous and flinty limestone. The characteristic features for field identification are (*a*) abundant chert nodules, (*b*) the occurrence of coral reef structure and heads of corals, Favosites helder-

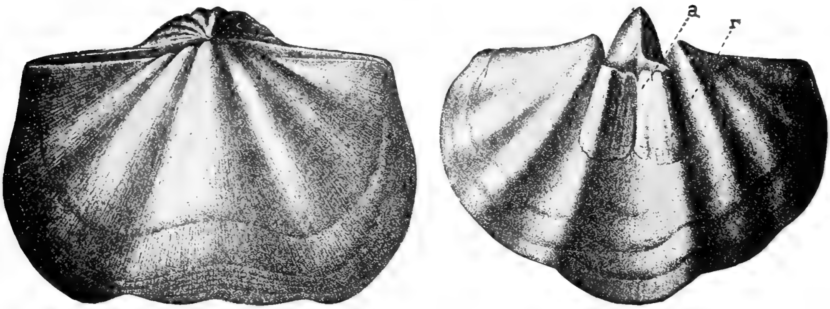


Fig. 5 Spirifer macropleura (Conrad), the most characteristic index fossil of the New Scotland beds in the Rondout region

bergia. The brachiopods Sieberella galeata and Atrypa reticularis are very common.

This formation has a thickness of about 80 feet and is rather distinctly separated from the underlying Manlius. The Coeymans is considered the base of the Devonic system of New York. It is

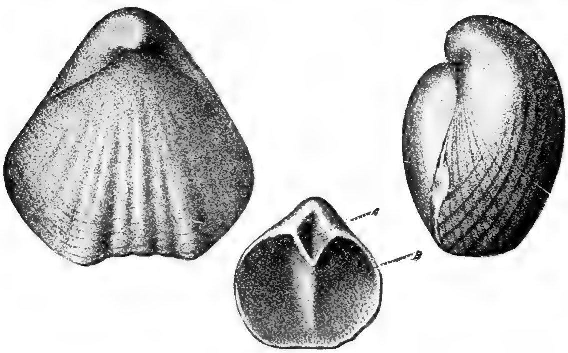


Fig. 6 Sieberella galeata (Dalman), the most reliable index fossil of the Coeymans limestone of the Rondout region

perfectly conformable upon the underlying series and it is evident that in this region there was no important break in the progress of deposition.

e **Siluric strata.** (17) *Manlius limestone.* Lime mud rock, fine textured, dense, with plainly marked sedimentation lines, gray to dark gray color. The most characteristic features in the field are (*a*) fine texture, (*b*) sedimentation lines, as if laid down in quiet waters as a lime mud, (*c*) solution joints sometimes enlarged to

cavelike form into which surface streams disappear (such as Pompey's cave near High Falls), (*d*) mud crack surfaces (in lower beds), (*e*) occurrence of the fossil Leperditia alta.

Its abundant jointing and the tendency to develop solution cavities from them is considered an objectionable character.

(18) *Cobleskill and cement beds* (limestone). It is not possible without the most painstaking, comparative, chemical and paleontologic research to differentiate the cement layers from the inclosing beds and to assign them all to the subdivisions that are recognized in some previous publications,[1] as the (*a*) *Rondout* cement (*b*) *Cobleskill* limestone, (*c*) *Rosendale* cement, and (*d*) *Wilbur* limestone. There are, however, two workable natudal cement beds, both at Rondout and at Rosendale, with a nonworkable layer between each case, and also one between the lower and the next underlying formation. Whether the two cement beds at Rondout represent the *Rondout* and the *Rosendale* horizons with the Cobleskill between, or whether they should both be regarded as *Rondout* with Cobleskill below, can not concern our present problems. And again, whether or not the two cement beds at Rondout are the same two that appear at Rosendale, or whether they are equivalent only to the upper one with a new lower bed (The *Rosendale*) added in this area and then with the Cobleskill between these two as claimed by Grabau, does not alter the plain fact that the whole series is a physical unit. It is a gray, rather close texture limestone, resembling the Manlius proper, and contains few fossils. It is perhaps even better yet to group all of these limestone beds below the Coeymans into a single unit and call it the Manlius series.

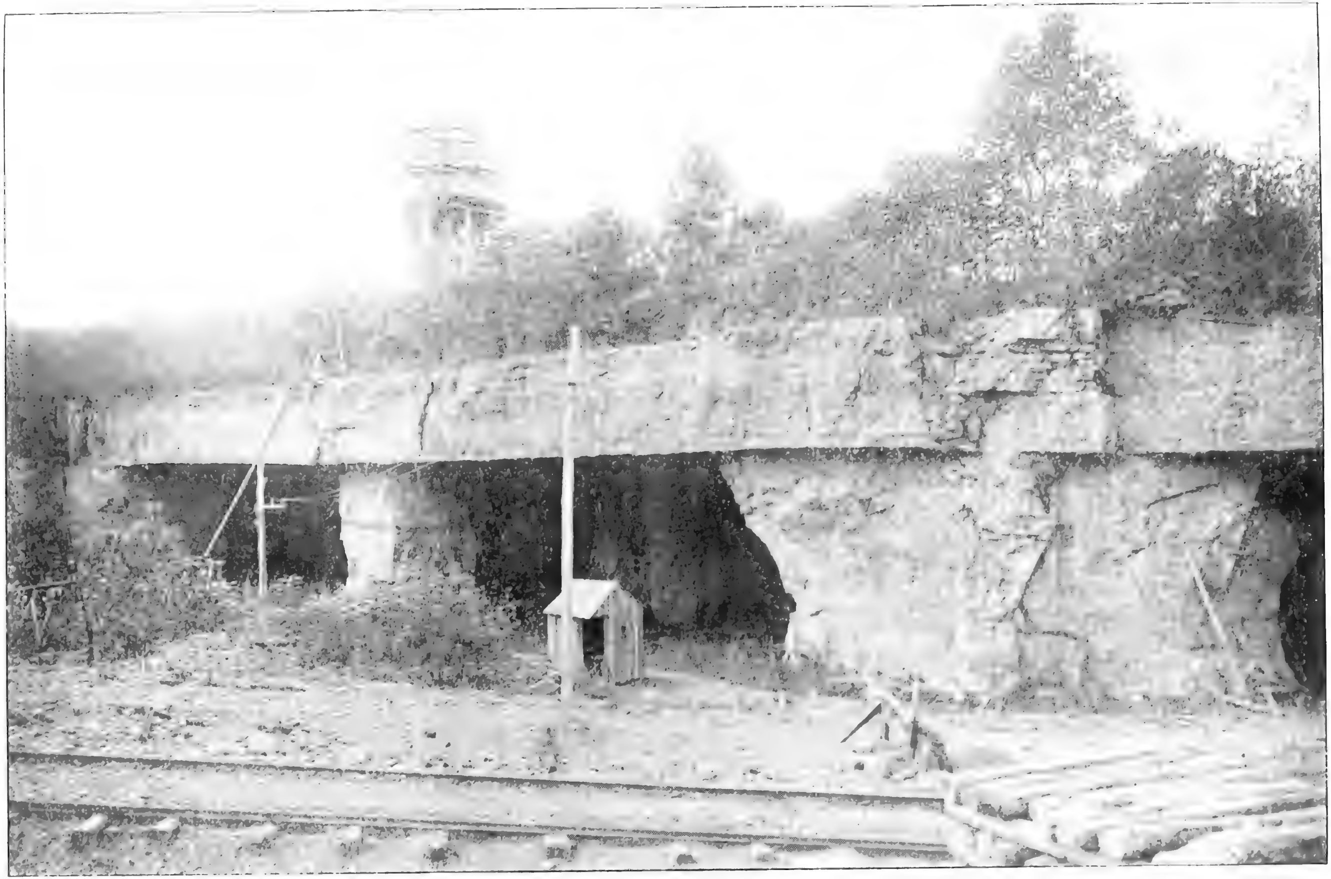
(19) *Binnewater sandstone.* Below the Manlius cement rock series lies the 60–100 foot Binnewater. It is chiefly a well bedded quartz sandstone, almost a quartzite in the upper beds with more shale in its lower portion, in color varying from white to greenish yellow and brown. The rock is rather porous in certain beds and especially along the bedding planes and is not well recemented where crushed by crustal movements. It is confined to the Rondout valley.

(20) *High Falls shale.*[2] Greenish to red argillaceous to sandy shales. The exposures are often a brilliant red while the rock

[1] N. Y. State Mus. Bul. 92 (Grabau), p. 311–13; N. Y. State Mus. Bul. 80 (Hartnagel), p. 355–58; N. Y. State Mus. Bul. 69 (Van Ingen and Clark), p. 1184, 1185.

[2] The term given by Hartnagle. N. Y. State Mus. Bul. 80. p. 345.

Plate 5



Limestone beds of the Rosendale cement region. The Beach mine near Rosendale. (Photograph by T. C. Brown for the Board of Water Supply)

Plate 6

Interior of the Norton cement mine, Binnewater, N. Y., showing the thickness and dip of one of the cement beds and the method of mining. (Photograph by T. C. Brown for the Board of Water Supply)

from drill cores is seldom highly colored. The protected beds are more commonly greenish in color and contain much iron sulphide. Occasional thin limestone beds occur in the upper portion at High falls — one of 4 feet forms the lip of the lower fall. The High Falls shale is confined to the Rondout valley and on the line of the aqueduct is 67–100 feet thick.

(21) *Shawangunk conglomerate.* The Shawangunk is a conglomerate and sandstone. The constituent pebbles are almost wholly quartz, well worn, and varying in size from that of sand to pebbles of several inches diameter. But for the most part the pebbles are small, abundantly mixed with sand, bound together by a silicious cement. Rarely a true quartzite is developed and still more rarely a shaly facies. The rock is therefore very hard, brittle, and in the undisturbed portions fairly impervious and resistant. But it suffers from crushing along zones of disturbance in folding and faulting and these zones are very imperfectly recemented. It is a durable rock, very resistant to ordinary decay, but forms great talus slopes. It is used for buhrstones (millstones), etc. It varies in thickness on the lines of the aqueduct from 280–400 feet. The rock is limited in its northward extension to this district — southwestward it is much more broadly exposed in the continuation of the Shawangunk range.

The Shawangunk completes the conformable Siluro-Devonic series down to the erosion interval at the close of the Ordovicic. The series of conglomerates, sandstones, limestones, and shales make an imposing column approximating 3000 feet of strata differentiated with more or less ease into 15 separate and mapable formations and a possible 5 or 6 more with careful paleontologic work. The series begins with the capping beds of the Shawangunk range and its northward extension toward the Hudson river at Rondout and Kingston, and thence westward constitutes the rock floor while its structures control the surface configurations far beyond the limits of the region under consideration. Immediately to the north and partly within the area here treated is the famous Rosendale cement region, the pioneer cement district of America and for many years the best producer. The strata used are almost exclusively the upper members of the Siluric ("cement beds") closely associated with the Cobleskill between the Manlius proper and the Binnewater sandstone. Rarely the Becraft from the Devonic series furnishes some cement rock.

f **Cambro-Ordovicic formations.** Between the Precambric metamorphics of the Highlands beneath and the Siluro-Devonic

sediments of the Shawangunk range and the Catskills above, lies a series of quartzites, limestones and slates less complexly disturbed than the older and more disturbed than the younger series — set off from both by unconformities representing time intervals that cover both folding and erosion. They are of more than 4000 feet thickness — how much more it is impossible to estimate because of the obscurity of data in the slates. There are very few fossil forms preserved in them. The series is, however, readily and sharply separable into three formations that may be mapped upon lithologic characters alone. They are of most importance in the Wallkill valley, Moodna creek, Newburgh, Fishkill, New Hamburg and Poughkeepsie districts. Their character, structure, and conditions have required careful consideration in the decisions on the Wallkill and Moodna siphons and in the discussions on the proposed Hudson river crossings [*see* Hudson river crossings, pt 2].

(22) *Hudson River slates.* The upper member of the Cambro-Ordovicic series is in itself complex. Prevailingly it is a slaty shale, occasionally it is a sandstone or shaly sandstone, or a simple shale; still more rarely it is almost a true slate, and very rarely a phyllite. The constituents vary from prevailing clay to quartz sand repeatedly in almost every locality. It is probable that as a rule the upper portions are the more heavily bedded and arenaceous. The rock is excessively affected by the dynamic movements that have at least twice disturbed it. A slaty cleavage in the more argillaceous members is most noticeable, but almost everywhere the strata are strongly tilted, crumpled, broken, faulted, or crushed in a most confusing way. This together with an original obscurity in bedding, and the obliteration by subsequent shearing of much that did exist, makes it impossible to reconstruct the complicated structure or compute the thickness of the formation. It is of such physical character as to absorb within its own limits much of the disturbing movements, and neither the formations above nor immediately below are so extensively and intimately affected. The formation is widely exposed and forms the bed rock over very large areas. Almost everywhere it is impervious to water, easy to penetrate by drill or tunnel, and resistant to decay. A few Ordovicic fossils may be found, the most characteristic being Dalmanella testudinaria.

(23) *Wappinger limestone.*[1] (In part Cambric, and in part

[1] The Wappinger Valley limestone of Dwight (1879) and Dana. The Wappinger limestone of Darton and others.

Plate 7

Bonticou crag. One of the peaks of the Shawangunk range. The rock is Shawangunk conglomerate. Bonticou tunnel passes beneath this point. (Photograph by Board of Water Supply)

Plate 8

A trench through Hudson River slates and sandstones for cut-and-cover aqueduct construction on the Newburgh division. (Photograph by Board of Water Supply)

Ordovicic). The formation is prevailingly of a compact, fine texture, dark gray, either massive or strongly bedded limestone. Where the stratification is very plain there are light and dark layers and an abundant silicious intermixture. In many outcrops the rock is so massive that even the dip and strike are obscure. Some places the rock is fine crystalline, almost a micromarble. On weathered surfaces it almost always exhibits a crisscross etching which marks the traces of rehealed cracks. From these it is seen that many of the apparently massive compact beds have at one time been extensively crushed. In many places there is scarcely a square inch wholly free from these evidences. The formation is best exposed in the wide belt that extends southwestward from the vicinity of Poughkeepsie and crosses the Hudson at New Hamburg into the Newburgh district. It undoubtedly underlies the slates in the rest of the adjacent area. There are few fossils and they are rarely found.

(24) *Poughquag quartzite.* Below the Wappinger limestone and upon the upturned and eroded edges of the Highlands gneisses lies a quartzite of variable thickness but which reaches at least 600 feet. It is a strongly silicified quartz sandstone — a quartzite by induration. It is strongly bedded but seldom shaly. Traces of schistosity may appear in certain zones and this is somewhat strongly developed outside of the area at the type locality (Poughquag, N. Y.).

Only fragments of trilobite spines have been found in this formation within the district.

g **Later crystallines south of the Highlands.** South of the Highlands proper except at one locality (Peekskill creek valley and its southwestward continuation through Tompkins Cove and Stony Point) the rocks are all much more thoroughly crystalline. There are two formations, and in places traces of a third, above the Grenville gneisses (Fordham gneisses and associates). These are known locally as *Manhattan* schist, *Inwood* limestone, and *Lowerre* quartzite. In Westchester and New York counties the quartzite is rarely found, and in a considerable proportion of those places where it does occur its relations are more consistent with the gneisses below than with the limestone-schist series above. This is true indeed of the type locality (Lowerre). There are, however, at least two points where the occurrence favors the reverse interpretation, so far as any is shown, and therefore a quartzite may be regarded as finishing the series, and making uncertain but probably unconformable contact with the underlying gneisses.

This series together with the gneisses below constitutes the bed rock and controls the underground conditions for all of the line south of the Moodna valley, 50 miles above New York. All of the southern aqueduct, and the New York city distribution conduits are wholly concerned with these rocks, and two divisions of the northern aqueduct have a large proportion of their work in them.

It is not wholly clear what age these crystallines represent. It is certain that the underlying gneisses are Grenville and that the metamorphic quartzite, Inwood, Manhattan series, is Post-grenville. It is possible that these latter are also Precambric. But usage following the correlations of Dana[1] and in the absence of as good evidence from any other source has regarded them as the Cambro-Ordovicic crystalline equivalents of the Poughquag-Wappinger-Hudson River series of the north side of the Highlands. The writer has elsewhere shown[2] that the evidence and arguments are not all on one side and that considerable doubt may still be entertained on that point. There is no object in following that argument here or in modifying the treatment here followed of making them a distinct series. Even if they should prove to be the exact equivalents of the Hudson River-Wappinger-Poughquag series the formations are physically so different and require so different treatment in discussion that they must for our present purpose be regarded as an essentially distinct series. From that standpoint alone the usage here followed is justified. The Manhattan schist of Westchester county as a type differs as much petrographically from the Hudson River formation of the Newburgh district as the Catskill formation of Slide mountain differs from the Jameco gravels of Long Island. In a discussion where physical or petrographic character is in control there is no doubt about the advisability of treating the two separately.

(1) *Manhattan schist.*[3] This is primarily a recrystallized sediment of silicious type. It occurs as a nearly black or streaked, micaceous, coarsely crystalline, strongly foliated rock. The chief constituents are biotite, muscovite and quartz. Quartz, feldspar,

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1 Dana, J. D. On the Geological Relations of the Limestone belts of Westchester county, N. Y. Am. Jour. Sci. 20:21–32, 194–220, 359–75, 450–56 (1880); 21:425-43; 22:103-19, 313-15, 327-35 (1881).

2 Berkey, Charles P. "Structural and Stratigraphic Features of the Basal Gneisses of the Highlands." N. Y. State Mus. Bul. 107 (1907), p. 361–78.

3 Manhattan schist of Merrill. N. Y. State Mus. 50th An. Rep't, 1:287. Same as "Hudson schist," of N. Y. city folio no. 83.

garnet, fibrolite and epidote also occur in large quantity. Occasional streaks or masses are hornblendic instead of micaceous. These are interpreted as igneous injections. They are especially abundant on Croton lake and near White Plains.

It is essentially a quartz-mica schist. But it is almost everywhere very coarse textured and hardly ever exhibits the fine grained, uniform structure of typical schist. Its abnormal make-up — the predominance of biotite and quartz — is the best defense for its petrographic classification. The abundance of mica makes it a tough rock but not very hard. The joints and fractures formed in later movements are not healed and zones of bad shattering are susceptible to considerable decay. These crushings are sufficiently common to encourage borings to tap their content of water for small family use throughout Westchester county; but they do not represent large circulation in any case. On the whole, the rock if fresh is good and durable. It may, though rarely, carry considerable sulphide. Practically all of the strictly original sedimentation marks are destroyed by metamorphism. The formation has great thickness, but because of the destruction of original bedding lines by recrystallization and additional complication by most complex folding, shearing, crushing and faulting, the structure can not fully be unraveled and the thickness can not be estimated with any approach to accuracy of detail. But there is probably a thickness represented of several thousand feet.

(2) *Inwood limestone or dolomite.* This formation lies beneath the Manhattan. It is everywhere coarsely crystalline either massive or strongly bedded, often very impure with development of secondary (recrystallized) mica (phlogopite) and other silicates, especially tremolite. It is essentially a magnesian limestone or dolomite in composition. There is an occasional quartzose bed in the midst of the limestone as at East View. The upper beds are most charged with mica and occasionally beds attacked by alteration have much green, flaky chlorite. There are occasional interbeddings of limestone and schist as a transition facies.

The coarser grades upon exposure to weathering readily yield by disintegration to a lime (calcite) sand resembling roughly an ordinary sand in general appearance. At Inwood, the type locality, this disintegration is so pronounced that great quantities are readily shoveled up and used for various structural purposes in the place of other sand. This dolomite is especially liable, as now shown by extensive explorations, to serious decay to great depth. The underground circulation seems to attack the micaceous beds with great

success and in some places the residue after this solvent action is of the consistency of mud. A nearly vertical attitude of the beds accentuates the opportunity. The most troublesome piece of ground encountered on the whole line of the New Croton aqueduct, constructed in 1885, was in a weak zone and crevice in the Inwood near the village of Woodland on the margin of the Sawmill valley [*see* discussions of Bryn Mawr siphon and New York city distributions in part 2].

The thickness probably varies but in many places where there is only a narrow limestone belt it is due more to shearing or faulting out than to original thinning. The most satisfactory estimates are based on the explorations at Kensico dam and the field observations at 152d street. They indicate an approximate thickness of 700 feet. But in all cases either the margins are obscured or there is possibility of faulting to modify measurements. There are no fossils. Weathering and erosion has almost everywhere developed valleys or depressions especially small tributary valleys in all formations, but as pointed out years ago by Professor Dana the principal valleys prevailingly coincide with the limestone belts.

(3) *Lowerre quartzite.* At Hastings-on-Hudson and again near Croton lake, there is a quartzite that appears to be conformable with the Inwood above. There is possibly more than 50 feet. It is a simple, clean quartzite. The other quartzites of Westchester and New York county have a more distinct relationship to the underlying gneisses with which they are conformable. The Lowerre of the type locality is of this second class. In the great majority of places where this bed would be expected to occur there is not a trace of it.

h **Older metamorphic crystallines (Grenville series).**[1] "The lowest and oldest, as well as the most complex in structure and rock variety, of all the formations of the Highlands region of southeastern New York is essentially a series of gneisses." Cutting these gneisses as intrusions of various forms are a great number and variety of more or less distinctly igneous types. In form they vary from small dikes or stringers to great batholithic masses; in composition, from the extremely basic peridotites or pyroxinites of

[1] This interpretation of the larger relations of the complex gneisses constituting the basis of the series, lying below the Manhattan-Inwood-Lowerre series, was presented by the writer under the title: Structural and Stratigraphic Features of the Basal Gneisses of the Highlands. N. Y. State Mus. Bul. 107 (1907). p. 361–78. The accompanying description is largely an abstract of this paper.

the Cortlandt series to the very acid granites of Storm King mountain or the granophyric pegmatites of North White Plains; and in relative age they likewise vary from a period antedating the chief early metamorphic transformation of the Grenville to Postmanhattan time. But these clearly igneous types attain a considerable prominence as separable units in the practical consideration of the problems of the project and on that account the chief ones will be more fully described under the next group.

The older portion — the various schists, banded gneisses, quartzites, quartzose gneisses, graphitic schists, and serpentinous and tremolitic limestone, forming the complex through which and into which the igneous masses have been injected — form together an interbedded series that was originally a sedimentary group. There is nothing known that is older in this region. Its characteristics and relations mark it as in all probability the equivalent of the "Grenville" of the Adirondacks and Canada.

No single type and no single characteristic can be given as a simple guide to the identification of this formation. The prevalence of certain varieties or groups of these and the strongly banded structure give a certain degree of character that forms a reasonable working base. The formation includes banded granitic, hornblendic, micaceous and quartzose gneisses; mica, hornblende, chlorite, quartz and epidote schists; garnetiferous, pyritiferous, graphitic, pyroxenic, tremolitic, and magnetitic schists and gneisses; crystalline, tremolitic, and serpentinous limestones, aphi-dolomites, serpentines and quartzites; pyrite, pyrohitite and magnetite deposits. This is the basal series. But it is complicated by a multitude of bands of granitic and dioritic gneisses that represent injections of igneous material at a time sufficiently remote to be subjected to most of the early metamorphic modifications. The equally abundant occurrences of quartz stringers and pegmatite lenses though of later origin can not be separated from this complex mass and the whole must be regarded as a physical unit. The occurrence of interbedded limestones and quartzites together with a variety of conformable schists and banded rocks, marks the formation as essentially an old recrystallized sediment.

No member of this older unit of the basal complex is sufficiently prominent to indicate a great break or change up to the time of the first great dynamic movements and igneous outbreaks. The following comparatively constant members are sometimes persistent enough to be considered formational units, but even more commonly

are obscure as to boundaries or are of too small development to map separately.

(4) *Interbedded quartzite.* Always a quartzite schist and always exhibiting conformity with the banded gneisses and schists. This is regarded as the uppermost member.

(5) *Fordham gneiss* (Banded gneiss). Granitic and quartzose black and white banded gneisses and schists of very complex composition and structure.

(6) *Interbedded limestones.* Crystalline. Interbedded, very impure, serpentinous and tremolitic, granular dolomites, usually 2 to 50 feet thick, possibly reaching a thickness of more than 100 feet in a few cases.

(7) *Older intrusive gneisses.* Variable types, mostly granites or diorites, strongly foliated sills.

Many are of very obscure relations. The line of close distinction between recrystallized sediment, segregations accompanying that change, and true igneous injection can not be drawn.

i **Special additional igneous types.** Under this heading are included the massive or little modified, not at all or only moderately foliated, igneous masses of later origin and local rather than regional development. In some cases, however, they are of decidedly controlling importance in the local geology and rise to the status of definite formations. The most noteworthy of these within reach of the aqueduct explorations are:

(8) The Storm King Mountain gneissoid granite
(9) The Cat Hill gneissoid granite (central Highlands)
(10) The Cortlandt series of gabbro-diorites (near Peekskill)
(11) The Peekskill granite (east of Peekskill)
(12) The Ravenswood granodiorite (Long Island City)
(13) The pegmatite dikes and lenses (segregational aqueo-igneous type)

(8) *The Storm King gneissoid granite* is one of the largest of the clearly igneous and less completely foliated types. It constitutes the whole of Storm King mountain and the larger part of Crows Nest on the west side of the Hudson, and, crossing the river, forms the chief rock of Bull hill and Breakneck ridge. It is a rather acid, coarse grained, reddish granite with considerable gneissoid structure in a large way [*see* Hudson river crossings, pt 2].

(9) *The Cat Hill gneissoid granite* is not essentially different from the Storm King type as a physical unit. Its occurrence at a

Plate 9

South portal to Garrison tunnel on the Peekskill division. The rock is a badly jointed granite belonging to one of the intrusives of the older gneisses. (Photograph by Board of Water Supply)

different point (Cat hill), widely separated by other types from the Storm King locality, and in rather large development, is worthy of separate note. It is cut, of course, in the long tunnel through Cat hill.

(10) *The Cortlandt series of gabbro-diorites* occupies an area of about 20 square miles between Peekskill and the Croton river, nearly all on the east side of the Hudson. It includes a very complete range of coarse grained, massive, igneous rocks from soda granites, grano-diorites and quartz-diorites to true diorites, norites, gabbros, pyroxenites, and peridotites. They doubtless represent stages or portions in the differentiation of a magma. The interrelations are only partially determinable, and the petrographic distinctions in detail are not useful here. The area occupied by the Cortlandt series has an uneven hilly surface with no structural trend, and makes the most striking contrast to the ridge and longitudinal valley structure of the rest of the region of the crystallines.

(11) *The Peekskill granite,* a white, or pink massive, very coarse grained, soda granite, occupying approximately 4 square miles immediately north of the Cortlandt area 2 miles east of Peekskill, is believed to be genetically related to the Cortlandt series. The evidence in favor of such a relationship has been gathered in the prosecution of this work and has not been published. But it may be said that the textures, structure, age, relationship to older crystallines, interrelations with the Cortlandt series, consanguinity of mineralogy, and composition all point toward the above relationship. In essential relations, therefore, it is the acid extreme of the Cortlandt series. Its economic features, however, are of sufficient importance and its easy differentiation from the regular Cortlandt types require that it should have separate treatment.

(12) *The Rravenswood grano-diorite* occurs chiefly in Brooklyn. It is a slightly foliated mass intrusive in the Fordham gneiss and is doubtless connected in origin with the sources of many of the hornblendic intrusive bands in the Fordham and Manhattan formations in the district. It covers a known area of about 5 or 6 square miles and may be more extensive. The rock is suitable for structural material and has required consideration in the study of " Distributary conduits " [*see* pt 2 East River section].

(13) *Pegmatites.* The pegmatites and pegmatitic granophyric masses of all kinds are of almost universal distribution in the foliated crystallines. They vary from quartz bunches or stringers to pegmatitic lenses and irregular masses, and to definite granitic

or pegmatic dikes. In many places they constitute a large proportion of the formation in which they occur. They doubtless vary in age, but for the most part seem to belong to the later period of metamorphism. Many of them are massive and largely free from foliation. They no doubt have a complex origin between simple aqueous segregation on the one side and true igneous intrusion on the other.

Summary of formations

Group a Quaternary deposits

(1) Glacial drift Till and modified drift, extra marginal outwash, sands and gravels, etc.	Occurs as a surface mantle over nearly all of the region under discussion, except the immediate sea margin

UNCONFORMITY

Group b Tertiary and Cretaceous deposits

(2) Tertiary outliers (*a*) Pliocene littoral deposits (Bridgetons?) (*b*) Miocene "fluffy" sand (Beacon hill) (3) Upper Cretaceous beds (*a*) Lignitiferous sand (marl series) (*b*) Matawan beds (clay marls) (*c*) Raritan (clays and sands)	Confined to Long Island, Staten Island and the New Jersey coast

UNCONFORMITY

Group c Jura-Trias formations

(4) Palisade diabase intrusion (5) Newark series of conglomerates, sandstones and shales	Confined to the west side of the Hudson south of the Highlands

UNCONFORMITY

Group d Devonic strata

(6) Catskill, white and red conglomerate (1725 feet) (7) Oneonta (upper flagstone) (3000 feet) (8) Ithaca and Sherburne (lower flagstone) (500 feet) (9) Hamilton and Marcellus shales (flagstone and shales) (700 feet) (10) Onondaga limestone (200 feet) (11) Esopus and Schoharie shales (silicious) (800 feet) (12) Oriskany and Port Ewen transition (100 feet) (13) Port Ewen limestone and shale (150 feet) (14) Becraft limestone (75 feet) (15) New Scotland shaly limestone (100 feet) (16) Coeymans cherty limestone (75 feet)	Confined to the Catskills, the Esopus and Rondout valleys, the northern extension of the Shawangunk range, and Skunnemunk mountain near Cornwall

Group e Siluric strata

(17) Manlius limestone (70 feet) (18) Cobleskill limestone and cement beds (30 feet) (19) Binnewater sandstone (50 feet) (20) High Falls shale, including small limestone beds (75–80 feet) (21) Shawangunk conglomerate (250–350 feet)	Confined to the Rondout and Esopus valleys and the northerly extension of the Shawangunk range, through the cement region of Rosendale, Binnewater, Rondout and Kingston, and a small outlier at Skunnemunk mountain

UNCONFORMITY

Group f Cambro-Ordovicic formations

(22) Hudson River slates, shales, and sandstones (very thick) (Ordovicic) more than 2000 feet (23) Wappinger limestone (1000 feet) (in part Cambric and in part Ordovicic) (24) Poughquag quartzite (600 feet) (Cambric)	Especially prominent as surface formations in the Shawangunk range, the Wallkill valley, and the region eastward and southward to the Highlands, on both sides of the Hudson

Group g Later crystallines (South of the Highlands)

(Uncertain age)

(1) The Manhattan schist, a thoroughly and coarsely crystalline sediment of uncertain age — generally supposed to be equivalent to the Hudson River slates, (Ordovicic) but here separated without necessarily raising that question because of their very different physical and petrographic character (2) Inwood limestone (or dolomite), a magnesian crystalline limestone of uncertain age, generally supposed to be the equivalent of the Wappinger (Cambro-Ordovicic), but here enumerated separately without necessarily raising that question because of their very different lithologic character and associates (3) Lowerre quartzite, an occasional quartzite of uncertain relations and very limited development	Confined to the region east of the Hudson river and south of the Highlands proper, occupying the region from the Highlands to Long Island

UNCONFORMITY

Group h Older crystallines (Highlands gneisses)

(Grenville series of metamorphics and intrusives — Precambric)

(4) Interbedded quartzite. A quartzose schist (5) Fordham gneiss (chiefly sedimentary). Granitic and quartzose banded gneisses and schists of very complex development (6) Interbedded limestones (Grenville) associated with the Fordham gneisses	Grenville Series	Formations characteristic of the Highlands and some of larger ridges extending southward to New York city. A series, which in petrographic variety, is as complex as all of the rest of the formations of the region together
(7) Old intrusions. Large and variable masses of granitic gneisses of igneous origin cutting the Grenville series, such as Storm King granite, Cat Hill granite, etc.		Postgrenville in age

Group i Special additional igneous types

(8) Storm King gneissoid granite, Storm King-Breakneck district (9) Cat Hill gneissoid granite. Garrison district (10) Cortlandt series of gabbro-diorites. Peekskill-Croton district (11) Peekskill granite. A boss, related to the Cortlandt series. Peekskill district (12) Ravenswood grano-diorite. A boss. Brooklyn, Long Island City and Southern Manhattan (13) Pegmatites. Dikes, lenses, segregations of general distribution	These are masses of strictly igneous origin (except the pegmatite) and of larger development which either because of their abundance (*pegmatites*) or large area (*Cortlandt*) or economic features (*Peekskill*) or important bearing upon the plans of the aqueduct (*Storm King*) are worthy of separate note.

3 Major structural features

In addition to the simpler structural characters of the strata, already sufficiently emphasized in the individual descriptions, there are numerous others of more general relation whose value and influence it is necessary to consider in many of the practical problems. Those of most importance are the unconformities, folds and faults. They are directly related to continental elevation and subsidence, to mountain forming movements and denudation processes, to metamorphism and to igneous intrusion.

a **Sedimentation structures.** In the younger strata the principal structures are those of bedding, stratification, conformable succession, etc., characteristic of all sediments of such variety of type. These are prominent in the older groups of formations down to the crystallines, but the earlier Paleozoics are also affected so profoundly by folding and faulting that attention is more concerned with these induced or secondary structures.

b **Unconformities.** Time breaks, with more or less disturbance of strata and accompanied by erosion, are numerous.

(1) That between the glacial drift and the rock floor is the most profound. It causes the glacial drift to lie in contact with every formation of the region from the oldest gneisses of the Grenville series of the Highlands to the traces of Miocene beds of Long Island.

(2) The interval between the Pliocene and the Upper Cretaceous beds is more obscure and hardly reaches the importance of an unconformity. It is probably more nearly of the value of a disconformity or of an overlap, and the very limited development of the overlying beds in the region gives little chance for determining relations in much detail.

(3) The overlap and unconformity between the Cretaceous and Triassic. A condition determinable only on the New Jersey side of the Hudson river.

(4) The unconformity between the Triassic and underlying formations of different ages. An interval representing mountain development and extensive erosion, in which the chief movement probably belongs to the close of Paleozoic time and includes the Appalachian folding.

(5) Unconformity between Siluric and the Ordovicic strata. An interval representing mountain development, folding and erosion, in which the movement known as the Green Mountain folding took place.

(6) Unconformity between the Poughquag (Cambric) quartzite and the underlying crystallines. An interval in all observable cases of great length and profound changes involving mountain folding, metamorphism of the profoundest sort, and extensive erosion.

(7) Among the crystallines of the south side of the Highlands there is one break of similar importance, between the Inwood limestone and the underlying gneisses. Whether or not it is the same as no. 7 above is not clear, but even if it represents the same break the relations are somewhat different in degree and character because of the lack of quartzite in almost all cases.

Within the gneisses of the Grenville series and their associates of all kinds there are no breaks of the unconformity type known. The contacts are eruptive in character, or are displacements instead.

c **Folds and mountain-forming movements.** All of the formations from the oldest up to and including the Lower Devonic strata are folded. Many of the smaller (minor) folds exhibit complete form in the stream gorges of the district, but all of the larger ones, the main folds, have in earlier time been eroded to such extent that the series is beveled off and only the truncated edges are to be seen, exhibiting strata standing more or less perfectly on edge, and making restoration of the form a very difficult or impossible task. This is only partially accomplished in the Siluro-Devonic margin along the Shawangunk range; it is more complete in the Cambro-Ordovicic north of the Highlands, and it reaches its most perfect development in the crystallines of the Highlands and New York and Westchester counties. These differences correspond roughly to the differences in age of the strata, and, taken together with the evidence of the profound unconformities, indicate that mountain-forming movements of far-reaching importance visited the region no less than three times. Each time of such disturbance, of course, the underlying older series was affected by the movements of that epoch in addition to any previous ones, and as a consequence the older is to be expected to show more complexity of such structures. Each succeeding series separated by such activity is therefore one degree simpler in structure.

Of these three epochs of great disturbance, one is (1) Precambric and corresponds to the time interval marked by the unconformity between the Poughquag quartzite and the gneisses; a second (2) is Postordovicic and corresponds to the time interval marked by the unconformity between the Hudson River slates and the Shawan-

gunk conglomerates, and the last (3) is Postdevonic (probably Postcarbonic, judging from neighboring regions of similar history) and has left as its most important evidence in this district, the excessively complicated sharp foldings and thrusts of the Shawangunk range and its extension in the Rosendale cement district.

Kinds. As to forms produced there are no usually described types that are not to be found here. The simpler forms of anticlines and synclines, both open and closed, symmetrical and unsymmetrical and overturned, are all common. The isoclinal is common in the gneisses. In each epoch of folding the compression forces were effective chiefly in a northwest-southeast direction producing arches and troughs whose axes trend northeast-southwest. This is the trend of the main structures throughout the region.

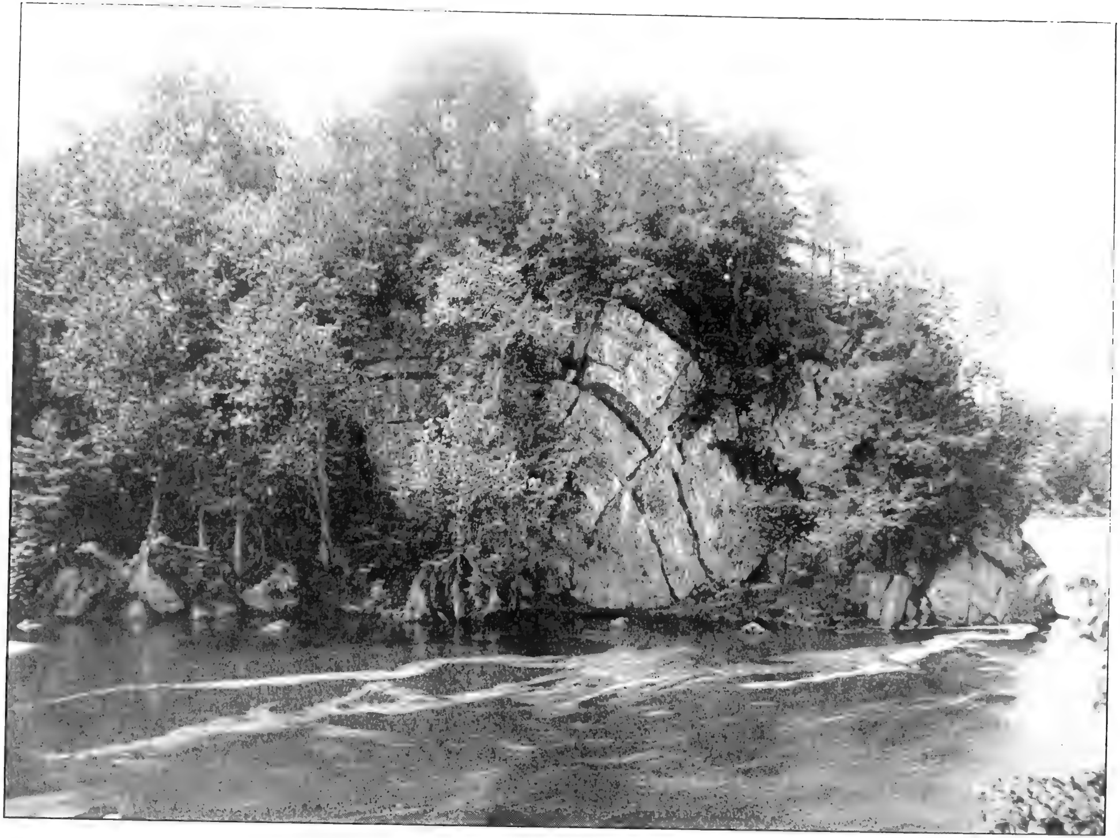
The extent of crustal shortening accomplished by this series of compressions is undetermined, but that it amounts to a total of many miles is indicated by the fact that over broad areas the strata stand almost on edge. Furthermore, in the older Highlands and in portions of the Hudson river districts the folds have been slightly overturned so that commonly the strata on both limbs dip in the same direction (toward the southeast). This seems to indicate a strong thrust from the southeast. All stages between the gentlest warping to strongly overturned folds, and from minute crumbling to folds of great extent and persistence are to be seen.

The effect of all the folding is chiefly to present a series of upturned strata to erosion and encourage a subsequent development of valleys along the softer beds bordered by ridges of the more resistant types.

As the axes of the folds lie in a northeast-southwest direction, this gives a marked physiographic development of ridges and valleys of the same trend, a most conspicuous topographic feature of southeastern New York.

d **Faults.** Accompanying the folding in each epoch, and especially the stronger overthrust movements there has been a tendency to rupture and displacement. These breaks are known as faults. Multitudes of them are of minute proportions and practically neglectable in a broad view, but many also are of large extent, traceable across country for many miles and indicating displacements in some cases of many hundreds of feet. For the most part these faults are of the thrust type and wholly consistent with the folds in origin. They run generally in a northeast-southwest direction, especially the larger ones, and frequently form the separation planes between different formations. Occasional cross

Plate 10



A fold in the New Scotland limestone on Rondout creek. (Photograph by Columbia University Summer School in Geology, 1908)

Plate 11

A thrust fault in the limestone beds on Rondout creek near Rosendale. (Photograph by Columbia University Summer School in Geology, 1908)

faults occur (with northwest-southeast direction across the strike), but so far as is known they are always of minor consequence. In rare instances, the trace of a fault line on the surface describes curious curves, such as that at Cronomer hill above Newburgh, apparently inconsistent with the chief structural trend, but a study of the whole geologic relation in such cases shows them to be connected with the projecting spurs of underlying formations which in any large thrust movement plow their way with some success through the younger overlying, less resistant, strata. They differ in no material way from the other more simple looking lines.

Both normal and thrust faults occur, but the thrust type appears to be most common.

The amount of displacement or throw is extremely variable. The larger faults represent movements of several hundred feet. In rare cases the movement may be as much as 2000 feet.

The effects may be grouped as follows: (1) the appearance of formations out of their normal order, i. e. contacts between formations that do not normally lie next to each other; (2) the production of escarpments, i. e. steep cliff-bordered ridges; (3) the development of zones of more or less extensively crushed rock along the principal plane of movement; (4) the determination of location for stream courses and gulches and valleys that cross the formations.

All of these effects are more noticeable and better preserved for the later movements than for the earlier ones. Many of those dating back to the earliest epoch, affecting only the crystalline rocks of the Highlands, are not readily detected. Most of the breaks have been healed by recrystallization and the contacts are often as close and sound as any other part of the formation.

But this is not so true of the later epochs — and in them a good deal depends upon the type of rock affected. The more brittle and hard and insoluble types are more likely to still have open seams and unhealed fractures than the softer and more easily molded formations. In some of these, recent water circulation has still further injured the fault zones by introducing rock decay to considerable depth. Because of the more ready circulation in them, it is noticeable that some of the extensive decay effects are produced in crystalline rocks that otherwise very successfully resist destruction. On the whole the softer clay shales and slates are less likely to preserve open water channels of this sort than any other formation of the region.

No part of the region is wholly free from faulting effects, except perhaps a part of Long Island. The Catskills also are very little affected — so little that this type of structure has not require consideration in the vicinity of Ashokan reservoir. But all parts of both the northern and southern aqueduct system have had this feature to consider.

Further discussion of the specific local problems introduced by faulting and folding is given under the problems of part 2. A considerably more extended comment on the age of fault movement is given under the heading " Postglacial faulting."

4 Outline of geologic history

Most of the general features of geologic history have been involved more or less in the foregoing discussion. It is impossible to wholly separate matters that are so intimately interrelated even though it is convenient to think of or consider one phase at a time. But it may serve a useful purpose to summarize the steps of progress as illustrated by local geology from the earliest geologic time to the present.

a **Earliest time.** (Prepaleozoic, Agnotozoic, Proterozoic, or Azoic Era). There is little doubt that the oldest rocks known in this region are representatives of a time of regular sedimentation. Conditions favored the deposition of silicious detritus of variable composition with an occasional deposition of lime, nearly always in very thin beds. What these sediments were laid down upon or where they came from are unsolved questions. The remnants of them that are still preserved are the basis of the " Grenville series " as interpreted in this area, and are the basal (oldest) members of the " Fordham " or " Highlands gneisses."

How long ago this series was deposited is not known. It can be stated only approximately even in the rather flexible terms used in historical geology. It is older than any Paleozoic strata (Precambric), probably very much older. It is even possible that this series is as much older than the Cambric as that period is compared to the present. In short, it is not known, and there is apparently little immediate likelihood of finding out even to which of the several subdivisions of the Prepaleozoic this series belongs. It is certain that before the Cambric sandstones of the Paleozoic era had begun to form, this older series was disturbed by crustal movements, folded, metamorphosed, intruded by igneous injections, elevated above the water (sea) level of that time and eroded by surface agencies. These movements and steps there is no doubt of.

When subsidence[1] again depressed the area beneath the sea the deposition of sands that we now call Cambric (Poughquag) quartzite began.

b **Early Paleozoic time.** With the sedimentation upon this old crystalline rock floor a long time of apparently continuous deposition began which ultimately resulted in the accumulation of several thousand feet of sandstones, limestones, and sandy or clayey shales that are now known as the Cambro-Ordovicic series (Poughquag-Wappinger-Hudson River series). But at the close of Ordovicic time or late in that period another crustal revolution began. The whole region was again compressed into mountain folds, faulted, sheared, metamorphosed, elevated above sea level, and subjected to erosion. This corresponds to the Green mountains folding of Vermont.

With the next subsidence and a return of sedimentation a new series began to form. The break marking the occurrence of all these changes, known locally as the Postordovicic unconformity, represents a considerable portion of Siluric time.

c **Middle Paleozoic time.** The earliest deposits of this series, which continued to accumulate through late Siluric and all of Devonic time, were heavy conglomerates very unevenly distributed over the new rock floor. These are the so called Shawangunk conglomerates, a formation that within the boundaries of this immediate area and within a distance of 20 miles varies from a thickness of more than 300 feet to almost nothing. But for the most part, sedimentation was regular and fairly continuous and of immense volume. The whole series of conglomerates, sandstones, shales, grits and limestones belonging to the later Siluric and the Devonic are included. Not all are believed to be marine however. The Catskill and Shawangunk conglomerates may well be of continental type.

Long after the deposition of all of these strata another crustal disturbance, for at least the third time, repeated the process of mountain-folding and erosion. This was the time of the Appalachian mountain-folding. In this region it caused a wonderfully complex development of folds and faults that are especially important and determinable as to type and age in the Rondout cement region. The movement, of course, affected all of the older formations as

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[1] There may possibly be an intermediate stage, practically a duplication of the whole as given above, between the very oldest and the Cambric, represented in the "later crystallines," but this may as well be neglected for the present.

well, but on them, already disturbed by earlier displacements, the features chargeable to the disturbance can not always be distinguished from older ones. All three of the mountain-forming compressions seem to have been controlled by the same relationship of forces and adjustments of movement, for the results are in each case the production of folds or faults of similar orientation and a final structure of uniform trend.

Deposition had been going on for ages, chiefly on the west and north side of the older crystallines; but with a return of sedimentation a decided reversal is noted. The Atlantic border is depressed and much of the interior region seems not to have been subjected to further deposition from that time even to the present.

d **Mesozoic time.** Again conglomerates, sandstones and shales were laid down upon an eroded floor. From their condition and lithology it is believed that they are partly of continental, flood plain, origin. The series is thick, generally assigned to the Triassic period and is extensively developed. During the time of accumulation and to some extent subsequent to it, there was extensive igneous activity pouring out and intruding basic basaltic matter in large amount. The Palisade diabase sill, and the Watchung Mountain basalt flows are the best examples.

At a later time small faulting occurred making frequent displacements in this series. But mountain-folding has not again visited the region. Such breaks as there are, are of the nature of overlaps and disconformities rather than of the revolutionary history indicated by a true unconformity. One of these intervals occurs in the Mesozoic between the Triassic and Cretaceous. Above it the thick series of Cretaceous shales, marls, sands and clays are developed. Succeeding this series a similar interval represents the earliest Cenozoic time.

e **Early Cenozoic time.** The earliest Cenozoic (Eocene and Oligocene) has no sedimentary record within this region.

There are small remnants of deposition representing Miocene and Pliocene time. Above these again the record is blank up to the time of the glacial invasion.

f **Late Cenozoic time — glacial period.** By some combination of conditions not very well understood, the chief features of which no doubt are,—(1) continental elevation and (2) shifting of centers of precipitation and (3) modification in the composition of the atmosphere, a period of excessive ice accumulation was inaugurated. Ice finally covered immense continental areas and

from its own weight by continuous accumulation spread out (flowed) from great central areas toward the margins. There is clear evidence of interruptions or advances and retreats of this general movement many times. But the same type of work and similar results were attained in each case. The chief features of this work was the moving of rock material frozen in the ice to long distances and the deposition of it again, more or less modified by its contact with the ice or by the effect of water upon its release, at other places and with entirely new associations. The tendency to ice accumulation was finally overcome to sufficient extent for the inauguration of the present condition of things. Whether it is a permanent change or only an interglacial interval is not clear. But the ice has withdrawn to the mountains and the polar north at the present time. It has not occupied the surface of this region probably within the last 40,000 years, and perhaps for a much longer time.

5 Outline of geographic history — physiography

The surface features of a country are the result of the working out of a long and complex series of processes with and upon the materials of the rock floor or bed rock. The relationship of surface features to the formations that occur in the rock floor and their stages of development, in short, an interpretation of their origin and meaning, constitutes geographic history or physiography. It differs little in essential character from geologic history, of which it is only a special branch, i. e. the history of surface configuration. And it can not be appreciated or understood except in the light of a thorough knowledge of stratigraphic and structural geology. In individual cases or particular regions the geologic knowledge must also be specific.

a **Early stages.** Occasional glimpses of surface features, and some scattered facts about their development are to be gathered of older continental existence. Surface features characteristic of their time were developed in the great intervals between each successive period of continuous deposition. Traces of them are involved in the unconformities of the geologic column already shown in the discussion of geologic history. Hills, valleys, streams, shores and all the appropriate assortment of forms must have existed. But they could not have been like those of the present in many minor features — especially in arrangement and distribution — because the bed rock of those times had only in part reached the complexity of

structure and composition now belonging to it. Many items of importance are indicated in some of these early periods. For example, the sea encroached on the land borders repeatedly from the westward — especially throughout Palezoic times, while in Mesozoic and Cenozoic times the evidence of shiftings of sea margins is confined to the east and southeast borders, and likewise probably no near by place has been continuously beneath the sea.

But the unraveling of these conditions is obscured by subsequent events. Land surfaces that once were, became covered by later sediments. The physiography of those times, Paleophysiography, as well as paleogeography, is therefore a difficult and intricate line of investigation. With these ancient surfaces the dicussion of present features has little to do. Here and there the present surface cuts across and exposes the edges of an older one giving traces of the old profile; but in most cases it is so distorted by the foldings and other displacements belonging to a later period that a restoration of the original continental features is a task fit for the most highly trained specialist.

The surface as it now exists, and the rock floor modified only by the inequalities of the loose soil mantle, yields more readily to investigations of origin and history.

b **History of present surface configuration.** On some portions of the region there seems to have been no deposition since the close of Paleozoic time. Throughout most of Mesozoic and Cenozoic times, therefore, those regions probably have been continuously land areas (continental) and have been subjected to the agencies of erosion. This applies particularly to the Highlands region and the Catskills and the Shawangunk range and intervening country.

What the surface configuration was like in the early stages is wholly unknown. In the beginning, mountain-folding — the Appalachian folding — was in progress and the features were probably those of partially dissected anticlinal folds. With the progress of erosion the Triassic deposits were accumulated along the eastern border, probably on the continental slopes. Subsequently, further elevation extended erosion over the Triassic areas also and the Cretaceous beds were laid down on the margin. The general lines of development have been the same from that time to the present. Each successive important formation less heavily developed and forming a band outside of and upon the older one — the whole now constituting a series of successive belts the oldest of which is far inland and the newest at the sea margin.

Therefore, when long periods of denudation are referred to, it is well to appreciate that this is especially applicable to the interior, that the sea margins are comparatively new, and that certain of the inland areas were suffering erosion long before the rock formations that lie beneath and form the rock floor of the sea border districts were in existence.

Cretaceous peneplain. It appears from studies of these problems in a broad way, and, drawing upon generalizations from continental features of a much larger field than that of the present study, that the continental region of which this forms a part must, in the earlier periods, have remained in comparatively stable equilibrium for an extraordinarily long time. So long a time elapsed that most of the area was reduced by erosion to a monotonous plain (peneplain) at a very low altitude, probably not much above the sea (base level). Only here and there were there areas resistant enough or remote enough to withstand the denuding forces and stand out upon the general plain as remnants of mountain groups (Monadnocks). Possibly the Catskill mountains of that day had such relation.

This reduction of surface feature it is believed was reached in late Cretaceous time. The continent stood much lower than now. Portions that are now mountain tops and the crests of ridges were then constituent parts of the rock floor of the peneplain not much above sea level. This rock floor was probably thickly covered with alluvial deposits (flood plain) not very different in character from the alluvial matter of portions of the lower Mississippi valley of today.

Upon such a surface the principal rivers of that time flowed, sluggishly meandering over alluvial sands and taking their courses toward the sea (the Atlantic) in large part free from influence by the underlying rock structure. The ridges and valleys, the hills, mountains and gorges of the present were not in existence, except potentially in the hidden differences of hardness or rock structure. Such conditions prevailed over a very large region — certainly all of the eastern portion of the United States. This so called Cretaceous peneplain is the starting point in development of the geographic features of the present.

Continental elevation. Following upon this period of stability and extensive denudation came one of continental elevation. How much above sea level this raised the areas under present discussion may not be determined, but that it was a sufficient amount to

rejuvenate the streams and permit them to begin the sculpturing of the land in a new cycle of erosion is perfectly clear. As soon as the elevation and warping of the continental border made its influence felt in the increased activity and efficiency of the streams (rejuvenation) they began transporting the alluvium of their flood plains and to sink their courses through this loose material to bed rock. The final result of long continued denudation under these conditions in early Tertiary time was the removal of the loose mantle and the beginning of attack on bed rock (superimposed drainage). The streams formerly flowing on alluvium that had now cut down to rock found themselves superimposed upon a rock structure not at all consistent with their former courses. With the progress of erosion on this rock floor all these differences of structure, such as the differences in hardness of beds, the trend of the folds, the strike of the faults, the igneous masses, etc., were discovered and the streams began to adjust their courses to them. Valleys were carved out where belts of softer rock occur, ridges were left as residuary remnants where belts of harder rock exist, and the surface (relief) took on some of the character of present day lines. That is, the principal mountain ranges of that time were the same as those of today in position and trend; but they had not so great apparent hight because the intervening valleys had not yet been cut so deep. The principal escarpments of that time were due to the same structural lines as those of today, only they have shifted somewhat along with the general retreat of all prominences by the forces of weathering and erosion.

In the course of this work of sculpturing and the shifting of valleys and divides and escarpments and barriers into constantly greater and greater conformity with rock structure, it came about by and by that practically all of the smaller and tributary streams had so completely adjusted themselves to their geologic environment that their valleys almost everywhere followed along the softer beds (subsequent streams), the divides were chiefly of harder beds, the trend of both were almost everywhere parallel to the strike of the rock folds and other structures (adjusted drainage) This undoubtedly involved in many cases a very radical change of stream course, and in some cases an ultimate reversal of drainage to such extent that tributaries were deflected inland against the course of the master streams and in some cases actually flowed many miles in this reversed direction before finding an accordant junction (retrograde streams). At least three of the streams of

southeastern New York are still of this type — the Wallkill, the Rondout and the lower portion of the Esopus.

But the larger rivers, the great master streams, of the superimposed drainage system, in some cases were so efficient in the corrasion of their channels that the discovery of discordant structures has not been of sufficient influence to displace them, or reverse them, or even to shift them very far from their original direct course to the sea. They cut directly across mountain ridges because they flowed over the plain out of which these ridges have been carved and because their own erosive and transporting power have exceeded those of any of their tributaries or their neighbors. They are superimposed streams (not antecedent), they have, with their tributaries, settled down in the ancient plain, and, by their own erosive activity, have carved the valleys deeper and deeper, cutting the upland divides narrower and narrower until now only here and there a ridge or a mountain remnant stands with its crest or summit almost reaching up to the level of the ancient peneplain on which the work began. If the transported matter could all be brought back and replaced in these valleys the old plain might be restored, but the work would immediately begin all over again.

Of these great master streams the Hudson is the only local representative [*see* Study of the Hudson River gorge in part 2].

Tertiary incomplete peneplanation. Such processes, if allowed to continue on a stable continental region, would ultimately reduce the land for a second time to a monotonous plain (complete cycle of erosion). The beginnings of such a plain would be made in the principal stream valleys upon reaching graded condition. Their lateral planation and the development of flat-bottomed valleys would begin at about the level that the plain would stand in the final completed stage. The difference of elevation between the ridge crests or hilltops and these flat valleys, i. e. between the old peneplain and the new unfinished one would be an approximate measure of the amount of the continental elevation that instituted the new cycle.

But judging from such remnants of this later plain as are to be seen, the two, i. e. the old Cretaceous peneplain and the new Tertiary peneplain are not parallel. Toward the southeast, toward the sea, the older plain descends more rapidly than the younger and intersects it. Both pass beneath sea level in that direction. The difference between them therefore varies with locality from

o feet to perhaps 2000 feet within the borders of the area (continental tilting or warping).

Late Tertiary reelevation. Traces of such an intermediate and incomplete peneplain are to be seen in the compound nature of the large valleys of the present day. Most of them are essentially broad valleys into the bottoms of which narrower valleys and gorges are cut. The tops of the minor hills and ridges of the broad valleys represent the intermediate Tertiary peneplain that was interrupted in its development before completion (interrupted erosion cycle). The inner narrow valleys indicate that for the second time a regional elevation rejuvenated the streams and they began their work of cutting to a new grade. They have made a good beginning at this task, and as a consequence have carved some relief in the old valley bottoms. These new streams have not yet reached a graded condition.

When the glacial ice began to invade this region all of the surface features had had such a history. Leaving out of account minor fluctuations of elevation and depression, of which there may have been several of too transient character to make a lasting impression on the topography, the stages become comparatively few and the general tendencies are easily understood.

The measurable differences of elevation between the Cretaceous and Tertiary peneplains give some reasonable conception of the amount of the first continental or regional elevation. Concerning the altitude reached in subsequent regional elevation there is less certainty. None of the streams, not even the master streams such as the Hudson, reached grade, for it exhibits strictly a gorge type not only within the present land borders, but it is now known to show gorge development far beyond the present coast line. Judging from the Hudson, therefore, it seems necessary to conclude that this continental region stood at a much greater elevation in some portions of the later period than had formerly prevailed. Probably the maximum elevation immediately preceded the glacial invasion.

Conservative estimates as to the amount of elevation of that time in excess of the present would place it at not less than 2000 feet. Much more than that is believed to be indicated, possibly 5000 feet or more.

In the meantime, the master stream, the Hudson and several of the tributaries cut into their valley bottoms to such extent as to make typical gorges so deep that their beds now, since the sub-

sidence, lie much below sea level. The Hudson bed is of this character throughout its course from Albany to the Atlantic, and in the Highlands, 60 miles inland, the known rock bed at one point is more than 700 feet below sea level.

In late glacial time there was still greater subsidence (50–100 feet) than the present as is indicated by terraces above present water level and the deltas formed at the mouths of tributary streams.

Such in general outline is the history of successive conditions governing the topographic development of the rock floor. The succession of periods of stability, elevation, stability again, reelevation and subsidence have had an effect on all sorts of formations, but the extent of the impress and its permanence varies greatly in the different districts. It is not possible to study these differences in detail here. They are the minor and special local characters that are in control at particular localities. In discussions of special problems some of these are taken up in more detail. But in each case the general history as outlined above, together with the modifying influence of known local structure and stratigraphic character are the foundations of a working understanding [*see* Hudson River crossings, Moodna creek, Rondout valley, etc., pt 2].

Pleistocene glaciation. An additional modification and one largely independent of and largely inconsistent with the distribution of the smaller features of the rock floor is introduced by the glacial drift. It covers almost everything, but so unevenly as to largely destroy some of the detail. It is in places more than 350 feet thick (as in the Moodna and Rondout valleys) and in others it amounts to nothing. It covers the narrow ravines and gorges heaviest and has altered the courses of many of the smaller streams, the original channels being hopelessly buried. The result has been chiefly one of reducing the ruggedness of outline that prevailed along the newer gorges of late preglacial time.

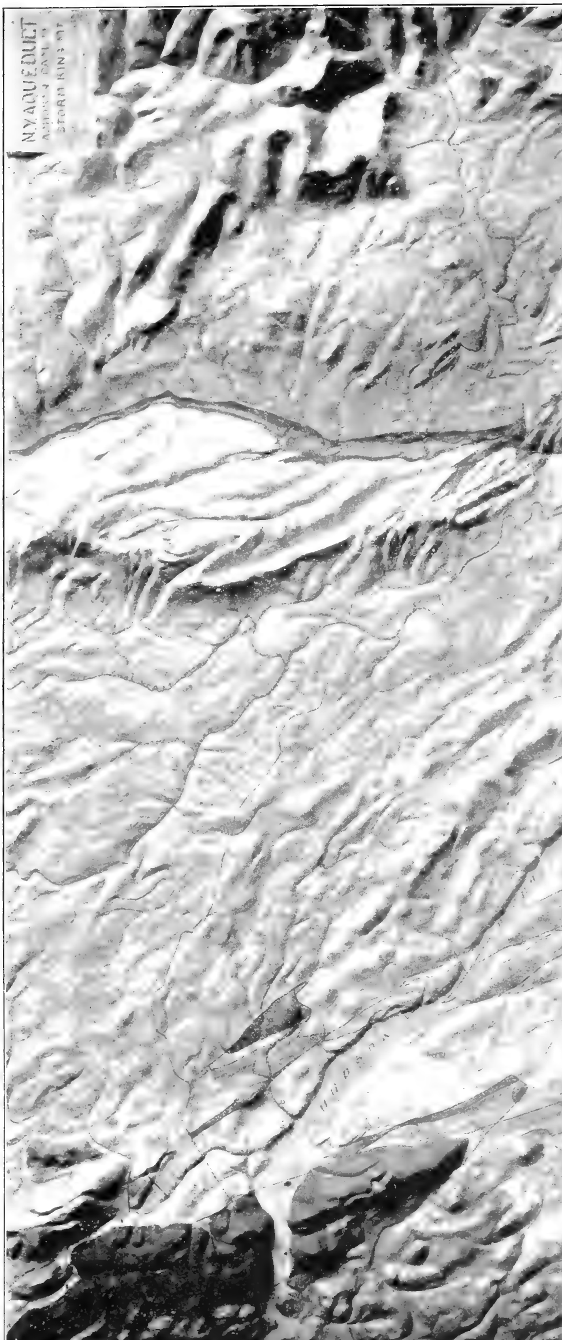
Besides this the usual surface forms characteristic of glacial deposits, occur — the kame, the drumlin, the esker, the hill and kettle topography of the terminal moraine, the overwash plain, the delta, the lake deposit and the gentle undulations of the ground moraine. These are superimposed on the rock floor features. Both are equally important to understand in the problems that have been encountered. Which set of factors is to be most regarded in a given case depends wholly upon the locality and the kind of enterprise or work it is proposed to undertake.

c **Physiographic interpretation.** Rock floor contour is an expression of the differences in character and structure of the bed rock formations themselves, brought about by ordinary surface weathering and transporting agencies, varied in their action and effects only by certain differences in elevation above the sea. It is apparent therefore that it would be possible by careful observation of surface features to gather data sufficiently definite to furnish a basis for suggestions about hidden and hitherto unknown or undiscovered structural and stratigraphic characters. But the application of it to practical engineering problems is a complicated and difficult matter. And this difficulty is nowise simplified by the occurrence of a drift soil that tends to obscure many of the more delicate features. For example, the later narrow stream gorges marking the stage of extreme regional elevation are completely buried. Only an occasional stream like the Hudson has maintained its course unchanged and has begun excavating the channel again. But even in this case, as will be shown under a separate head, the work of reexcavation is only just begun and the amount yet to be done and the corresponding original depth of the gorge are wholly unknown.

Certain surface features, however, are readable and, considered with due regard for all possible causal factors, give very useful suggestions. From them one obtains clews as to (1) the attitude or relations of the hard and soft beds and the weak zones, (2) the dip and strike of strata, (3) the persistence of a formation, (4) the occurrence of faults, (5) the direction of the chief disturbances, (6) the resistance and durability of local rock types — in short the structural characters of all kinds because differences in the distribution of these characters have given the different topographic forms and geographic areas. They have made the features of the Highlands look different from those of the Catskills, and those of Wallkill valley different from the Croton. Because of the long train of conditions with which these surface features are each involved and the structures that they indicate they become easily the chief factors in preliminary judgment of comparative practicability of rival locations, and are the most reliable guide to direction and character and extent of exploratory investigation for many engineering enterprises.

d **Physiographic zones.** In summarizing the physiographic data it appears that the following belts or zones may be regarded as fairly distinct units:

Plate 12



Relief map of the region from the Catskill mountains to the Highlands showing the principal physiographic features. (The original model shows also the areal and structural geology.) (Taken from model made in the physiographic laboratory of Columbia University by Messrs Billingsley, Grimes and Baragwanath)

(1) *Coastal plain.* A district underlain by Cretaceous and later rocks and confined to a part of Staten Island and Long Island, not exceeding 400 feet relief. This zone is characterized by dendritic drainage, except a narrow belt on its inner margin which is a longitudinal valley of the "inner lowland" type. Long Island sound occupies the position of this old adjusted valley.

(2) *Piedmont belt.* A district lying between the coastal plain and the Highlands. It is underlain chiefly by crystalline rocks and metamorphosed sediments. Not exceeding 800 feet relief. It is characterized by adjusted drainage obscured only by drift. The ridges and valleys trend northeast and southwest close together and with very little variation on the east side of the Hudson, while on the west side the gentle dips of the Triassic give broader and more unsymmetrical forms with dip slopes and escarpments wholly independent of the opposite side. The zone is essentially transitional between the simple forms of the coastal plain and the complex mountainous character of the Highlands.

(3) *Highlands.* The rugged elevated zone formed by the crystalline gneisses. Reaching elevations of 1600 feet. It is characterized by irregular mountain masses and lofty ridges of a general northeast trend but with many prominent irregularities both of form and of drainage. The valleys are deep and narrow. There are many steep escarpments. It is a mountainous zone in which complex structures and rocks have led to the development of complex forms. The zone forms a sort of barrier 20 miles wide across the Hudson river which exhibits its most zigzag and narrow and gorgelike development in this district.

(4) *Appalachian folds.* Characterized by folded Paleozoic rocks north of the Highlands. Reaching elevations of 1500 feet rarely — general relief 400–800 feet. North of the Highlands the relief is much less pronounced. The softer rocks of the early Paleozoic formations permitted the development of a broad valley with almost perfectly adjusted tributaries, most of which on the west side of the Hudson are reversed. The topographic forms give expression to the universal folding and faulting of the formations. It is essentially a transition from the complex mountain zone of the Highlands to the much simpler Catskill area.

(5) *Catskill Monadnock group.* Characterized by undisturbed Paleozoic strata and very strong relief — reaching elevations of 3500 feet. The eastern margin is an escarpment facing the Esopus and Rondout valleys which are adjusted to the gently dipping strata of that side. Over the rest of the district the beds lie so

flat that drainage is essentially dendritic modified slightly by jointing. The great relief of the Catskills is due wholly to erosion of flat but very resistant strata that withstood the destructive erosion of Cretaceous peneplanation and stand as residuary remnants even to the present time. The Catskills are therefore essentially a Monadnock group. In structure they are almost as simple as the higher portions of the cuesta of Long Island, and they hold the same relation to the forms developed by erosion out of the old Paleozoic coastal plain of the interior.

Summary

Physiographically the most complex zone is midway in the region under discussion — i. e. The *Highlands*. This belt is bordered on both sides by less complicated zones of less relief, of more regular topographic forms and less obscure history — the *Piedmont zone* on the south and the *Paleozoic folds* on the north. The outer margins are both simple, essentially eroded coastal plains with strata dipping away from the central belts and on which forms and drainage lines characteristic of such history are developed. These outer zones are the *coastal plain* of Long Island on the south and the *Catskill Monadnock group* on the north. It matters little that they differ in age by almost half of the known geologic column.

A view of the Catskill mountains looking across the Beaverkill basin which is to form a part of Ashokan reservoir

II

GEOLOGIC PROBLEMS OF THE AQUEDUCT

INTRODUCTION

The group of studies assembled in this part are chiefly those that have required considerable exploratory investigation in connection with the proposed Catskill aqueduct and that have furnished new data of a geologic character. In some cases the additional investigations have discovered new and wholly unknown structures or conditions and in all cases the features as now established are much more accurately known than would otherwise have been possible.

The benefits of the studies have been twofold and reciprocal. On the one side the practical planning of the enterprise has constantly required an interpretation of geologic conditions as a guide to locations and methods and on the other the extensive investigations carried on have given an opportunity for practical application of geologic principles under conditions seldom offered and the data secured in additional explorations serve to make the detail of some of these complex features now among the most fully known of their kind. Examples of such cases are (*a*) the series of buried preglacial gorges (as in the Esopus, and Rondout and Wallkill and Moodna valleys) and (*b*) the completed geologic cross sections (such as the Rondout valley, the Peekskill valley, Bryn Mawr, etc.) and (*c*) the numerous additions to the knowledge of local rock conditions (such as that at Foundry brook, Rondout creek, Coxing kill, Pagenstechers gorge, Sprout brook, and others).

Almost every locality has its own specific problem and its own peculiar differences of treatment and interpretation of features. Nearly all of the studies here presented came to the attention of the writer and others[1] in the form of definite problems or questions involving an interpretation of geologic factors and an application to some engineering requirement. Some of these questions, as is pointed out more fully in part 1, chapter 2, are (*a*) the location of

[1] Professor James F. Kemp of Columbia University and W. O. Crosby of the Massachusetts Institute of Technology and the writer constituted the regular staff of consulting geologists.

buried channels beneath the drift, (*b*) the character and depth of the drift, (c) the kind of bed rock, (*d*) the condition of bed rock for construction and permanence of tunnel, (*e*) the underground water circulation, (*f*) the occurrence of folds and faults, (*g*) the position of weak zones, (*h*) the depth required for substantial conditions, and many other similar problems.

These need not be treated in their original form. Indeed many of them have now ceased to be problems in any real sense, for subsequent provings have made them simple facts, and wholly new questions came to take their places. In some of the larger problems, however, it is believed that a treatment which involves a discussion of the original problem and the method of solving it, together with the data thus secured and the final interpretation of geologic features as now understood or established will be more instructive than a mere enumeration of the collected results.

So far as possible each problem is treated as a unit and fully enough to be understood by itself. But a general knowledge of local geology as outlined in part 1 is assumed.

CHAPTER I

GENERAL POSITION OF AQUEDUCT LINE

Surface topography constitutes the chief factor in determining the general course of the aqueduct. It is planned to control the water so that it will flow to New York city. There is therefore a gradual descent of aqueduct grade from 510 feet A. T. at Ashokan dam to 295 feet at Hill View reservoir. Wherever the surface of the country is approximately the same as the aqueduct grade for that district it permits of the so called "cut and cover" type of construction which is much cheaper than any other. Therefore, other things being equal, the position that will permit the greatest proportion of cut and cover work would have a decided advantage. So it is possible from any series of good topographic maps to lay out trial lines that are sure to be worthy of consideration. The topographic sheets of the United States Geological Survey and the maps of the New York Geological Survey are of great usefulness in such preliminary work.

But a little field examination shows that there are many other features and conditions that materially modify even comparative cost and are still more important factors in consideration of permanence and safety. Sometimes it is not apparent that a course has any objectionable features till considerable exploratory work has been done. Likewise a serious difficulty at one point may more than counterbalance advantages at some other, so that considerable portions of the line are finally shifted to a better average position. In the course of these preliminary explorations much valuable data have been secured that now relate to points a considerable distance off the present line. The information has, however, been necessary and useful.

One of the cases of this kind where geologic conditions have had an almost controlling influence is involved in the choice of place of crossing of the Hudson river. It has involved a shift of the whole line between the reservoir and the Highlands. Difficulties encountered in finding a crossing of the Esopus also contributed to the argument favoring a shift of the line [*see* map of trial lines west of the Hudson]. One of the points where exploratory work had reached definite results before the more southerly line was finally adopted is near West Hurley. Here wash borings

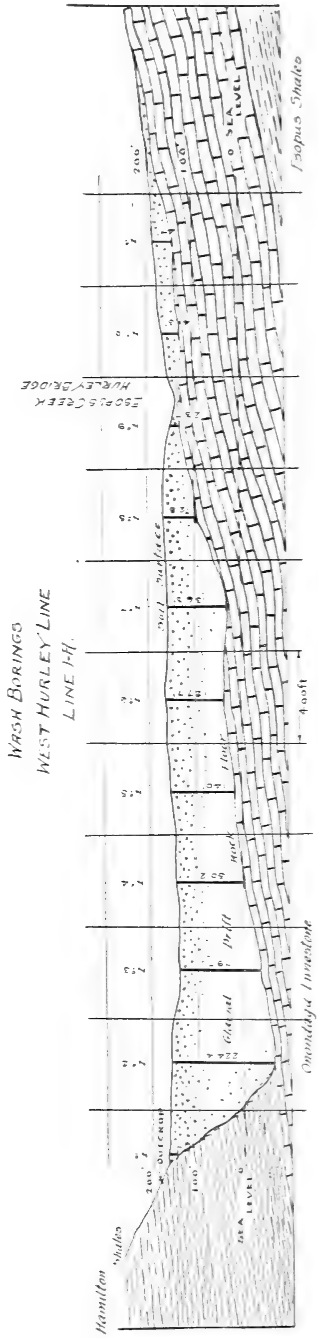


Fig. 7 Geologic cross section of the Esopus valley at West Hurley as indicated by a series of wash borings

were successfully put down through the fine sands and silts of the lower Esopus valley so as to give a fairly acceptable profile of the rock floor [*see* fig. 7]. Esopus creek in this portion of its course follows the Hamilton shales escarpment which forms a steep border on the west side, while the east border of the valley and floor are formed by the underlying Onondaga limestone. Gentle westerly dips prevail for both formations, so that in the perfect adjustment reached before the glacial invasion a cross section would have shown a typical unsymmetrical valley—one side a gentle dip slope and the other a bluff developed by the undercutting of the stream as it shifted against the edges of the shales.

Results of exploration show that the valley is filled to a depth of more than 200 feet with silts and sands that are essentially overwash and glacial lake deposits. The flat surface further favors this explanation as had been pointed out before any explorations were made. Later observations in that portion of the Rondout valley which is a continuation of this structural feature indicate similar deposits as far south as the new line at Kripplebush, 10 miles away.

In this instance at West Hurley by careful measurement of dips on the Onondaga limestone and the Hamilton shales it was possible to estimate the approximate depth to which the Onondaga floor rock would pass by the time the base of

the escarpment is reached. It was further believed that the covered portion is wholly drift-filled down to the Onondaga. It was easy therefore to estimate the approximate profile and suggest the point of greatest probable depth. The accompanying figure illustrates the form and structure of this valley. Each valley has had in a smaller way a similar study and adjustment of location of line.

The final result is shown on the accompanying map which indicates the course of the aqueduct as now being constructed.

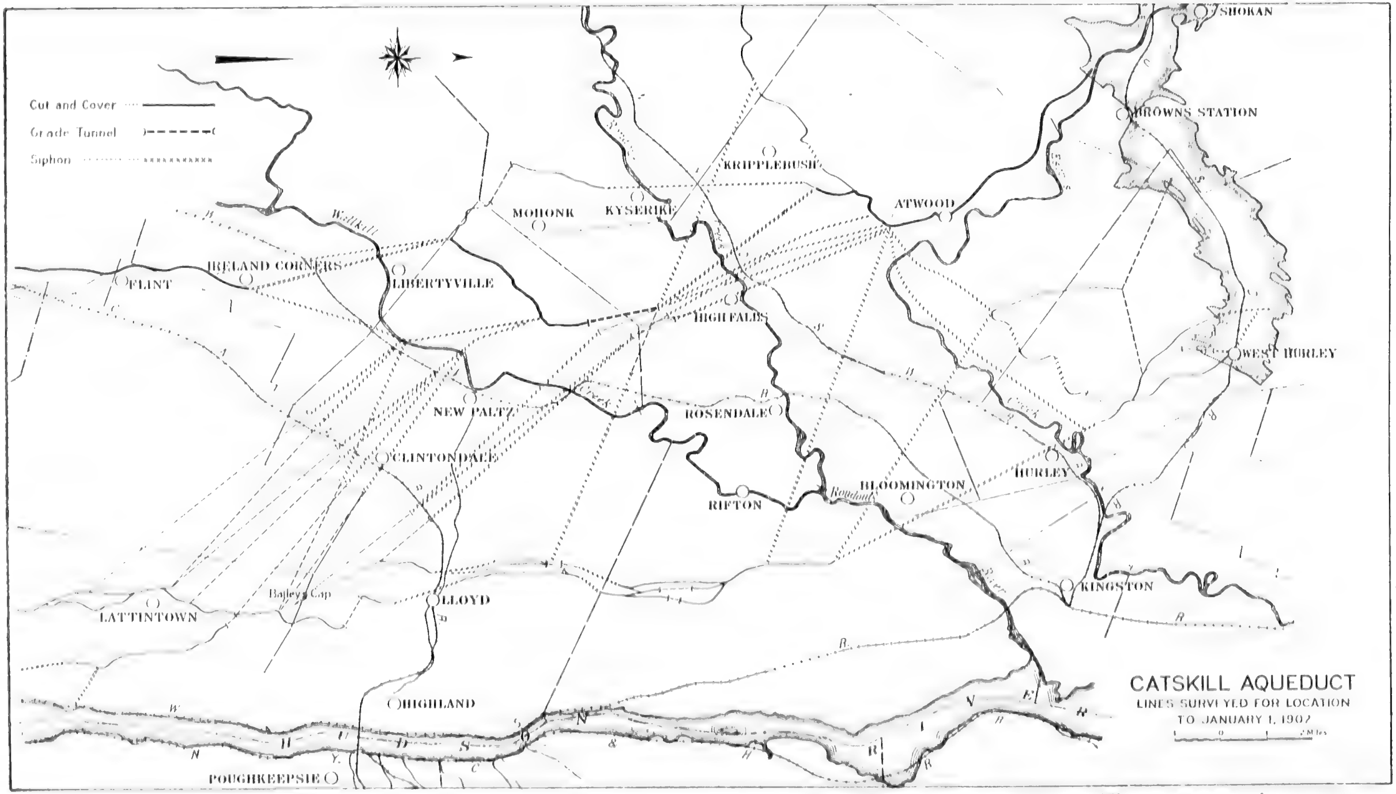


Fig. 8 Location map; showing lines surveyed for possible location and final line selected with its different types of construction — cut and cover, grade tunnel, and pressure tunnels. The line finally chosen passes through Atwood, a little to the west of High Falls and Libertyville, and through Ireland Corners. (By courtesy of the Board of Water Supply)

CHAPTER II

HUDSON RIVER CANYON

This is a special study of the Hudson river gorge[1] based upon explorations by borings at the several proposed crossings. Altogether 226 preliminary borings were made on 14 cross sections. The most important lines of borings are located at seven different points on the Hudson [*see* location map]. Four of them are in the vicinity of New Hamburg, lying not more than a couple of miles north and south of that village, while three others are located within the Highlands. [*See* comparative geologic study in following chapter.] The chief basis of information on all but one of these lines is the wash rig, a contrivance as already pointed out that gives rather incomplete data [*see* Relative Values of Data, pt 1]. On this account it is not possible to give the true bed rock profiles of the river canyon even approximately except at one location, i. e. the Storm King–Breakneck mountain line. An occasional diamond drill hole has been put down on some of the others and this has been done systematically at the Storm King location in a persistent effort to determine the gorge profile and bed rock condition.

The work already done has proven that in the Hudson at least the wash rig borings give wholly unsatisfactory profiles. The holes do not penetrate the boulders and heavy glacial drift that is now known to fill the canyon. The profiles, however, that were drawn from this sort of data have some value. They indicate that bed rock is still lower and that the finer silts extend down to these depths. In some places there is a heavier filling of 400 to 500 feet below them before the rock floor is reached.

Wherever the diamond drill has succeeded in reaching rock the formational identification has been made and the geological cross section is a little more complete. As a matter of fact, however, at almost every locality the structural relations are so complex or so obscure that they are still not fully known. The accompanying profiles and cross sections summarize the mass of accumulated data:

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1 Kemp, Prof. J. F. Buried Channels beneath the Hudson and its Tributaries. Am. Jour. Sci. Oct. 1908. 26:301-23. Some of the accompanying descriptions of river crossings follow closely this excellent summary of Hudson river explorations from Professor Kemp.

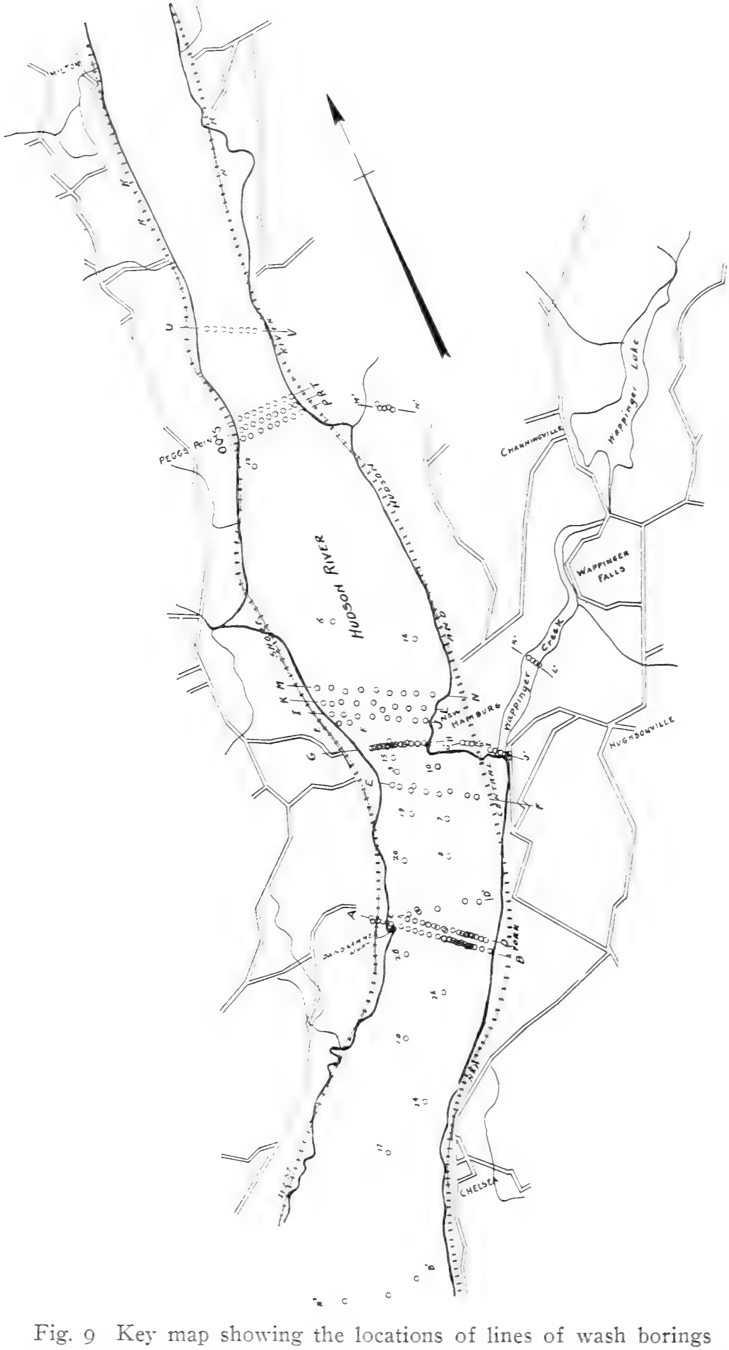

Fig. 9 Key map showing the locations of lines of wash borings forming the basis of the accompanying cross sections of the Hudson above the Highlands

I Points of exploration[1]

a **Tuff crossing.** This line is a half mile above Peggs point. Wappinger limestone forms the east bank of the river and Hudson river slates the western bank. There seems to be no abnormal structural relation of the formations. All data are from wash borings. The accompanying section gives the results.

b **Peggs point line.** Peggs point is 2 miles north of New Hamburg. At this location Wappinger limestone forms the east bank and Hudson river slates the west bank of the river as in the previous case. The limestone dips gently westerly while the slates have a variable attitude. This is a normal relation and there is no direct evidence of any great structural break. A large number of wash borings have been made and five diamond drill holes were driven, three of them in the river. None indicate a greater depth than 223 feet, although there is a wide stretch, 1040 feet, not explored by the diamond drill. This space must contain the deeper gorge if one exists here. From the known conditions at the entrance to the Highlands, 10 miles further down stream, where the channel is known to be more than 500 feet deeper, it may be rather confidently asserted that a deeper inner channel does exist at this point.

c **New Hamburg line.** This line crosses the Hudson from Cedarcliff to the village of New Hamburg. The river is narrow — only 2300 feet. There are no drill borings within the river channel, but there is one on each bank. Both penetrate Wappinger limestone first and then pass into Hudson river slates beneath. How much of a gorge exists here is wholly unknown except in so far as may be judged from the wash boring. There are the same reasons for believing that a gorge exists as those noted for the Peggs point line.

Structurally this line is probably the one of greatest complexity. It is however perfectly clear that the abnormal position of the slates and limestone on the east side of the river is caused by a thrust fault. A similar relation of the slates and limestone on the west side must be due to a like movement, but whether they are separated portions of the same structural unit or of two adjacent ones is not clear, although they are probably distinct

[1] All of these explorations on the Hudson river have been under the direct supervision of Mr William E. Swift, division engineer, in charge of the Hudson River division.

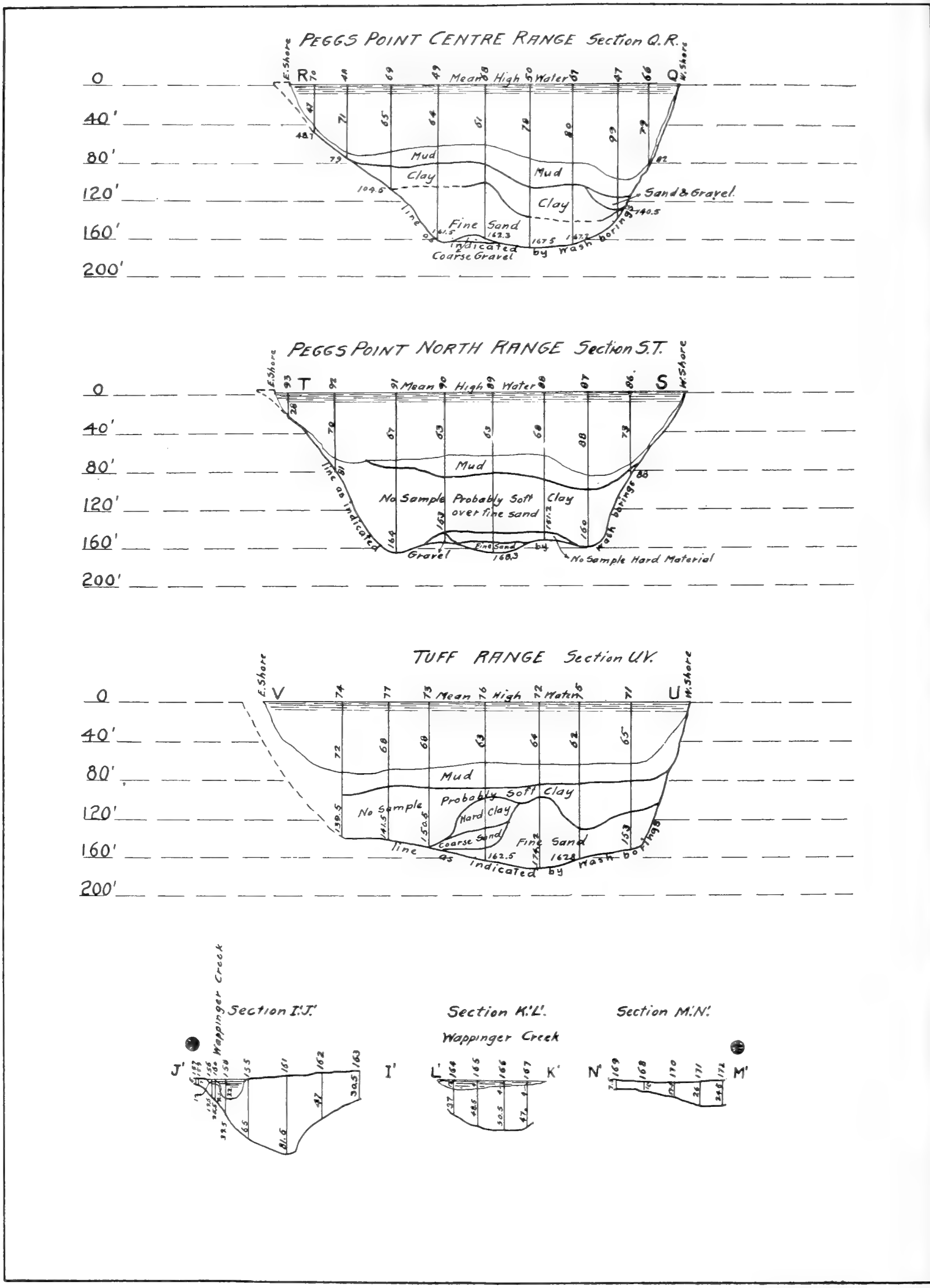

Fig 10 Cross sections of the Hudson river north of New Hamburg and of Wappinger creek based upon wash borings. [For locations *see* key map, fig. 9]

Five lines of wash borings were followed, and the results of these are indicated in the accompanying figures. A maximum depth of 263.5 feet is shown by these wash borings.

d **Danskammer line.** This line is about a mile south of New Hamburg. Two lines of wash borings were made, reaching a maximum depth of 268.5 feet. In this case slates standing almost vertical form the east bank and limestone dipping gently eastward the west bank of the river. Whether there is a deeper gorge or a more complex structure here is wholly unknown.

Of the three remaining lines, all of which are within the Highlands, that one projected between Storm King mountain on the west and Breakneck ridge on the east has been much the most thoroughly explored. It is known as the Storm King line. The other two have seemed to merit less attention. One crosses the river from Crows Nest mountain to Little Stony point and Bull mountain just north of Cold Spring, and is known as the Little Stony point line. The other crosses at Arden point about a mile south of West Point and Garrison.

e **Arden point line.** Only wash borings were made. A maximum depth indicated by this method is 220 feet. Structurally this location appeared to have disadvantages, and although the evidence as to bed rock conditions is confined to the natural outcrops, there is no doubt but that it has objectionable features of this sort.

The Hudson follows closely the structural control in this portion of its course. These structural elements include the foliation, the bedding of the original sediments, the subsequent shearing zones, and the strike of folds and faults. Crushed and sheared zones are nowhere in the Highlands seen so extensively developed as on the islands and the east bank of the Hudson in this, the central portion of its Highlands course. The river is very narrow, being only 2120 feet on this line.

f **Little Stony point line.** The river here is 2360 feet wide. The rocks on each side are similar and give no clue to possible depths of channel. Less than 200 feet was reached by the lines of wash borings. Three drill borings penetrated the stony or bouldery river filling somewhat deeper — one near the center reaching 322 feet. None, however, reached bed rock.

g **Storm King crossing.** Extensive exploratory work has been carried on at this point, both on the banks and in the river. Wash borings as usual have given poor results. Two diamond drill holes were run at an angle toward and beneath the margins of the

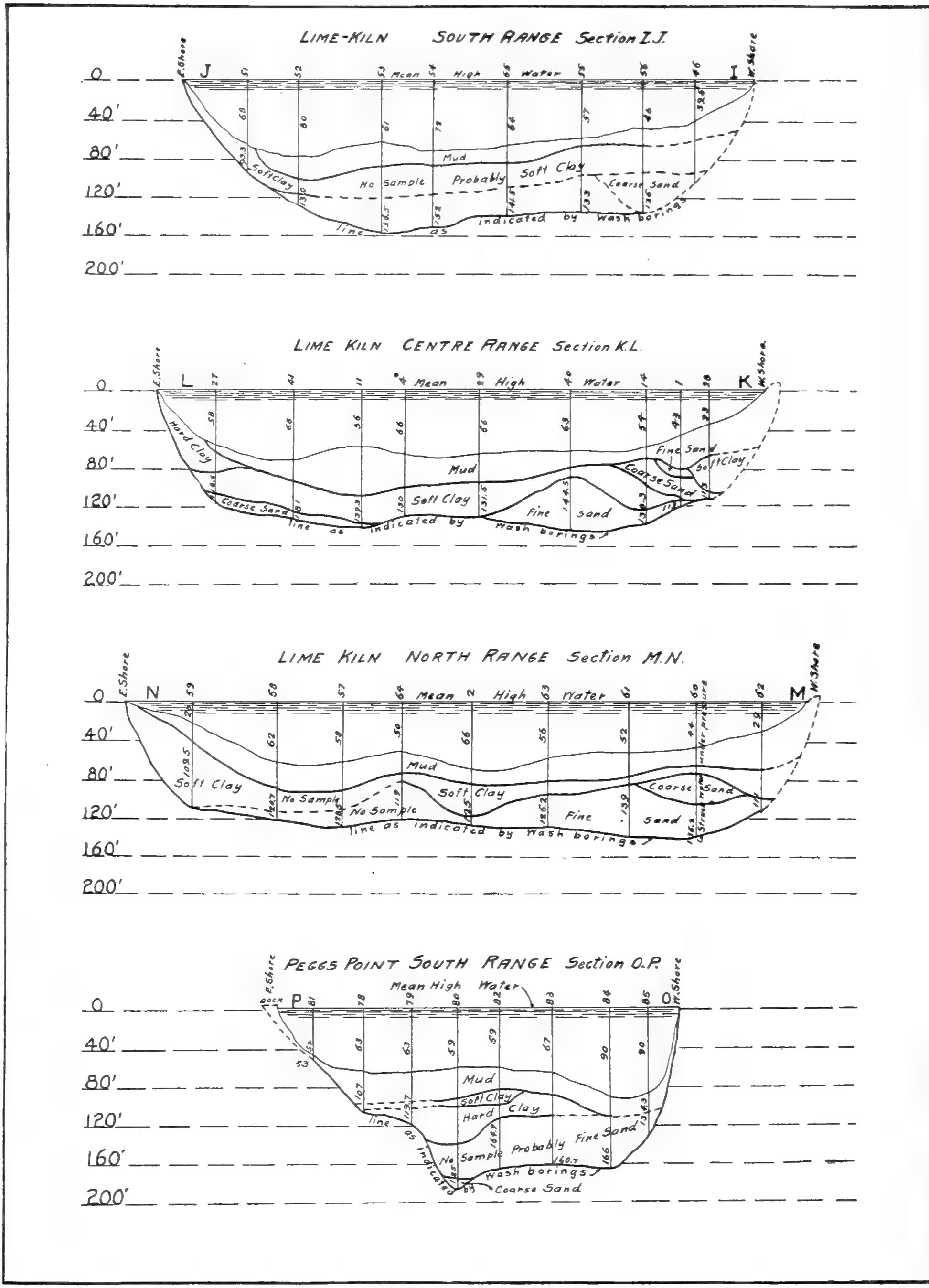

Fig. 11 Cross sections of the Hudson river near New Hamburg based on wash borings
[For locations *see* key map, fig 9]

river, and in addition a working shaft suitable for permanent use has been started on each side of the river. These have thoroughly explored the rock character to a depth of about 800 feet. It has proven to be of constant type, a gneissoid granite, affected by moderate amount of jointing, shear movements and occasional dike intrusion. The two sides are alike, the rock in depth is comparatively free from water, nearly all coming from the adjacent surface drainage.

Persistent efforts have been made to use the drill in the river to explore the rock channel, but with meager results. The difficulties to be overcome in drilling in this tidal river to the necessary depth are probably greater than have even been encountered in any similar undertaking. The disturbance presented by the current, the tide, the depth of water, the drift filling above the rock channel, and the traffic in the river are a constant menace. The complex character of drift filling in this gorge, especially the occasional heavy bouldery structure, makes it necessary to reduce the size and recase the holes repeatedly. But in this regard the work has suffered less actual loss than by the menace of river traffic. Several times after the greatest efforts had been put forth in pushing the drills deep into the gorge a helpless or unmanageable or carelessly guided steamer or scow has wrecked the work. In this way some of the most critical locations have been lost together with many months of labor.

The results are shown on the accompanying drawings.

It is worth noting that of those holes located far out in the river channel only two have reached bed rock. Even these two have penetrated the rock so little distance that there might be still some doubt of permanent bed rock. The fact, however, that the rock found is of the right type, i. e. like the walls of the gorge, leads to the conclusion that the bottom was actually penetrated. Neither of these holes are in the middle of the river, and, although the maximum depth of 608 feet was reached by one of them, the central portion of the buried channel proves to be still deeper. One hole located near the middle was able to penetrate to a depth of 626 feet without striking bed rock. But it was finally lost. The latest results are from a boring that has reached a total depth[1] (January 1, 1910) of 703 feet, the last 8 feet of which was believed by the drillers may be in bed rock. All above is drift and silt.

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[1] Subsequent exploration has proven that the bottom of the old channel lies still deeper. This boring has been pushed to a depth of 751 feet without yet touching bed rock (Oct. 8, 1910).

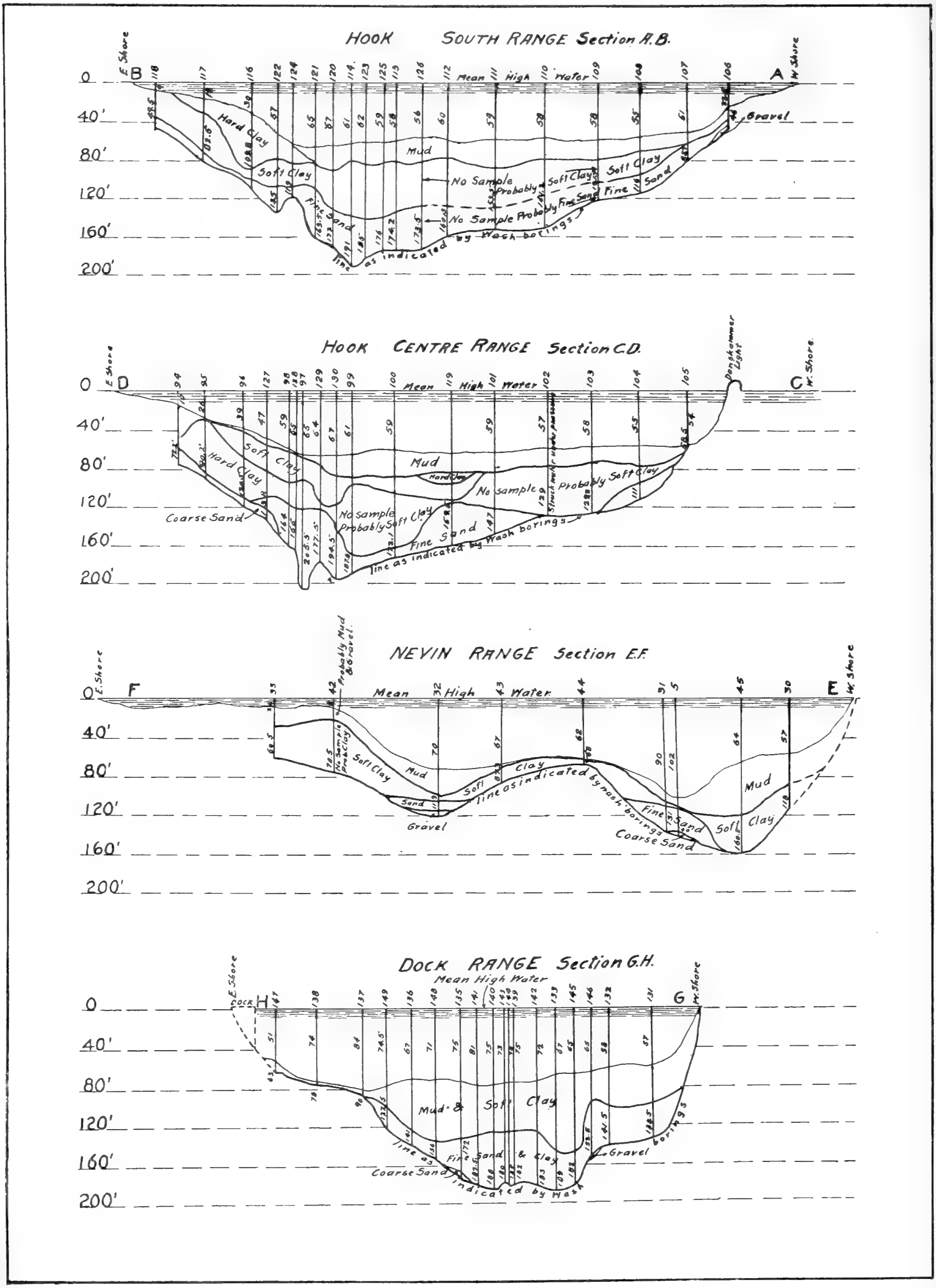
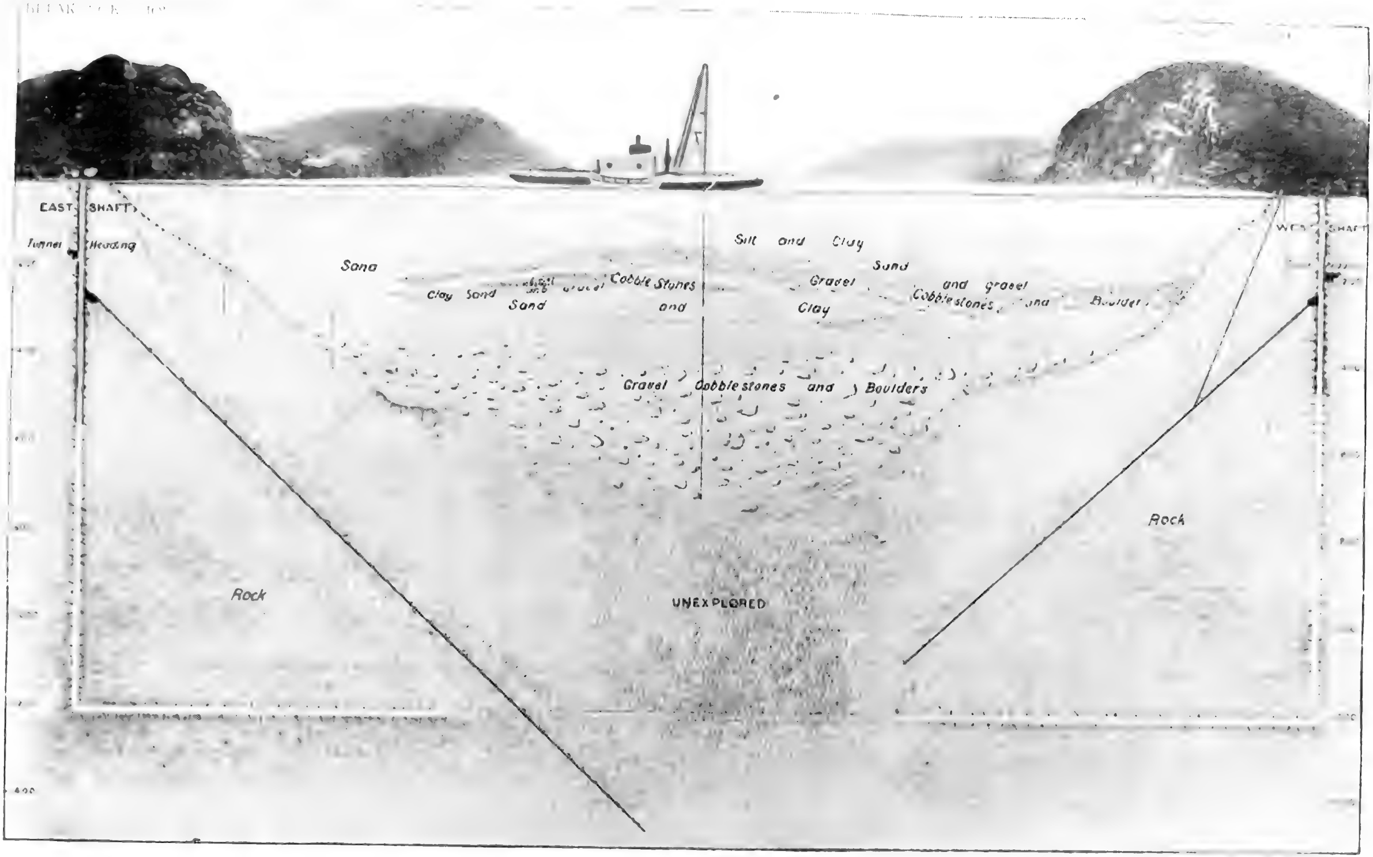


Fig. 12 Cross sections of the Hudson river at four points between Danskammer Light and New Hamburg [*see* key map, fig. 9, for locations]

Plate 14



A composite diagrammatic cross section of the Hudson gorge at the Storm King crossing showing the method of making the vertical borings, the direction of the first two inclined borings, the positions of the shafts and the extent of explorations. (Adapted from drawings of the Board of Water Supply)

2 Discussion

The present facts therefore indicate that the buried Hudson channel is more than 700 feet deep between Storm King and Breakneck ridge. Furthermore this is more than twice as great depth as has been found (so far as yet tested) at any other point either above or below this place. Although data of this kind are scarce yet there are two other borings that have given surprising results—(*a*) at Peggs point and (*b*) the Pennsylvania borings at New York city.

Peggs point. At this place, where studies were made for a possible crossing, a hole 700 feet from shore struck rock at 223 feet and the unknown space or interval within which it is possible for a channel to lie is less than 1040 feet wide. This is about 10 miles above the Storm King crossing and in much softer rock (Hudson River slates). Yet the Storm King gorge in granite is deeper than that (deeper than 223 feet) for a width of nearly 2500 feet. Of course, there may be, and probably there is, a much deeper channel at Peggs point within the 1040 feet unexplored space. But even so there is a remarkable discrepancy in width of gorge at these two points that must be accounted for in some other way than simple stream erosion.

The Pennsylvania borings opposite 33d st., New York city. The data gathered by the Engineers of the Pennsylvania Tunnel Company in their explorations for tunnel from 33d street, Manhattan, to Jersey City, have recently been made public. There are six holes into rock. Their positions and depth to rock bottom are given below:

a 800′ from New York bulkhead 190′ to bed rock = aplite

b 1000′ from New York bulkhead 290′ to bed rock = hornblende schist

c 2180′ from New York bulkhead 300′ to bed rock = chloritic and serpentinous rock.

d 2350′ from New York bulkhead 260′(?) to probable boulder = jasper breccia

e 3300′ from New York bulkhead 270′ to bed rock = arkose sandstone

f 13700′ from New York bulkhead 225′ to rock=brown sandstone

There are other shallower borings on both sides of the river. Those on the Manhattan side are represented by several different facies of Manhattan mica schist and granite and pegmatite in-

trusives, while the New Jersey side is represented by different varieties of arkose and gray and brown sandstone belonging to the Newark series.

It should be noted that although only one hole marks rock bottom as low as 300′ (that one situated 2180′ from the New York bulkhead about the middle of the river), yet there is at least a 1100 foot space on each side which is essentially unexplored, and within one of these spaces there may be a deeper gorge.

The cores taken from the east side of this middle zone belong to facies of the Manhattan schist formation, while those on the west side belong to the Newark series. The middle one, however, is essentially a soapstone or serpentine and may be a continuation of the Hoboken serpentine belt. In any case, it belongs in age to the older series of formations.

It is certain that here again, 50 miles below Storm King locality, a very deep gorge, if one exists, must be comparatively narrow.

Submarine channel. It is worth noting in this same connection that a submerged gorge has been mapped by the Coast and Geodetic Survey on the continental shelf from the vicinity of Sandy Hook to the deep sea margin, a distance of more than a hundred miles. This is interpreted by Spencer[1] and others with apparently sound argument as the lower portion of the old preglacial Hudson gorge formed during an epoch of great continental elevation. The outer portion of this submerged gorge is very deep. That section near shore is shallow and obscure. It has been assumed that this obscurity and shallowness is due to offshore and river deposition, filling the channel with silt. No better explanation is yet forthcoming. But even here the width of the submerged gorge is suggestive. In very much softer sediments than any encountered in its whole course on present land, and in a part of its course from 50 to 100 miles below the other sections, the river has cut a gorge only 4000 feet wide at top and 2000 feet deep within a broader valley 5 miles wide. In its deepest known part the proportions are 10,000 feet in width at top to 3800 feet in depth.

From this it would appear that the inner gorge type of development is characteristic of the Hudson, and that it was originally an exceedingly narrow one compared to the present river width, indicating rapid erosion during a brief and comparatively recent epoch. This submerged continental margin condition is favorable to the

[1] Spencer, J. W. The Submerged Great Canyon of the Hudson River. Am. Jour. Sci. 1905, v. 19.

Plate 15

The enlargement of the Hudson river known as Newburgh bay as seen from the northerly slope of Storm King mountain. This shows the gathering ground of the tongue of glacial ice that enlarged and overdeepened the Hudson gorge at the Gateway. (Photograph by Board of Water Supply)

assumption that there are narrower, still deeper channels within the unexplored spaces both at New York city and at Peggs point.

The only known exception and the one really surprising section is the Storm King crossing. It is too wide, considering the profiles at Peggs point and at New York city for simple normal stream erosion. That is clear enough. But a still more difficult question is whether it is also too deep. It is much deeper than any known section above or below for a distance of 50 miles.

There appears to be only one satisfactory explanation of this abnormal width of the deeper section and that is by glacial erosion. Just above Storm King is the wide bay opposite Cornwall and Newburgh. The few glacial scratches observed trend about s. 15° e. The ice therefore moved to the east of south, and it is noted that the course of the river is about the same. The northern front of Storm King mountain is steep and trends east and west while the northern front of Breakneck mountain trends southwest. It would appear therefore that these slightly converging mountain fronts served as sort of a funnel into which the ice was forced from the wide gathering ground immediately above, and through which there may have been a tongue or stream of ice of more than average power and efficiency moving almost in direct line of the present course of the river. It is reasonable to expect that these conditions would favor more than average glacial erosion.

3 Storm King–Breakneck mountain profile

It is practically impossible to draw a complete profile for the Hudson river gorge at any point in its lower course. Even at Storm King mountain or New York city or at Peggs point, at each of which places considerable exploratory work has been done, only the broadest features are known. Nevertheless, several things have been proven and they are worth considering in this question. They may be summarized as follows:

a If there is a very deep gorge at Peggs point (deeper than 250 feet) it can not be over 1000 feet wide.

b If there is a very deep gorge at New York city (deeper than 300 feet) it can not be over 1200 feet wide.

c At Storm King, located between the other two and in harder rock than either of them, a gorge at least 400 feet deep is proven to have a width of more than 1500 feet.

It is certain that simple stream erosion could not account for such a difference of cross section. There is no doubt but that en-

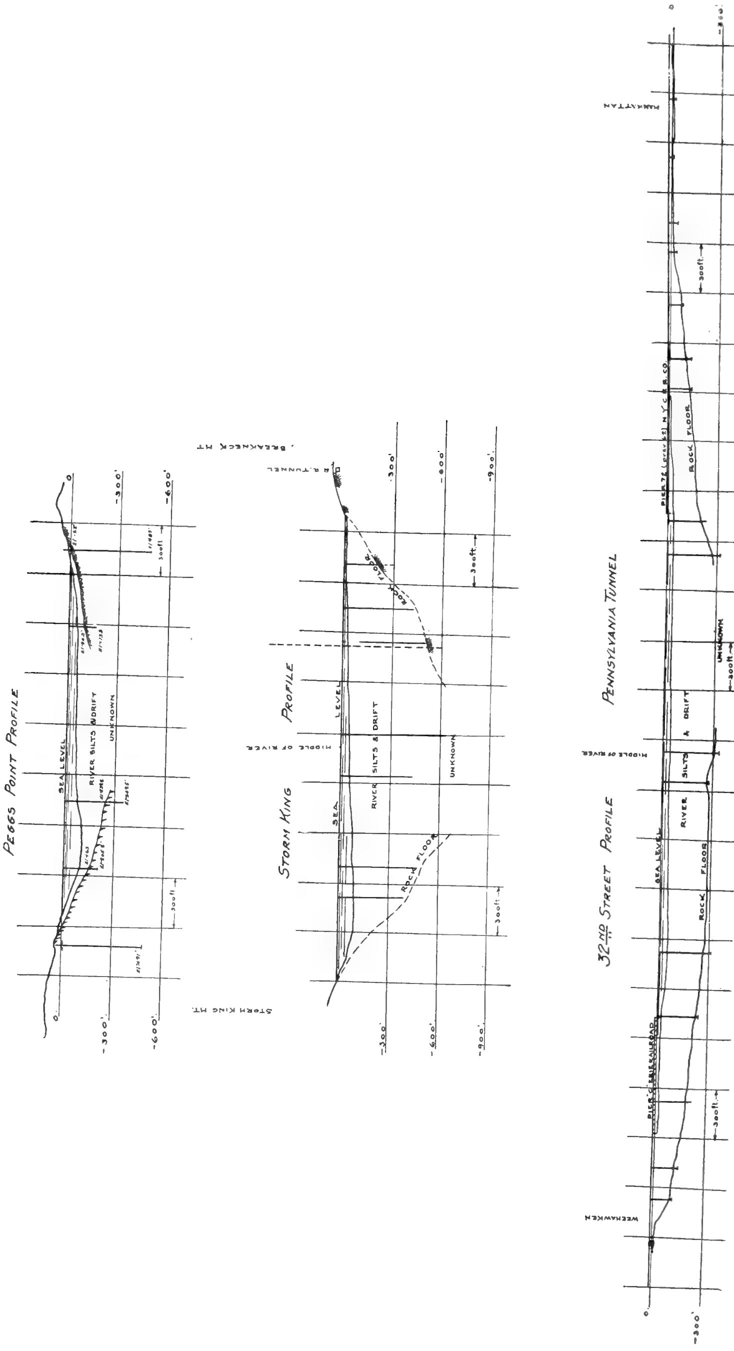


Fig. 13 Comparative sections of the Hudson gorge — at Peggs point, at Storm King and at 32d street, New York city — drawn to the same scale to show the remarkable size of the Storm King section below 300 feet

larging by ice so far as widening is concerned is practically proven. It may also be overdeepened, by which is meant that it may have been gouged out deeper than could have been done by a stream of water alone.

If ice action then be granted, the profile ought to be and probably is essentially an ice valley profile, i. e. of a more or less U-shape, rather than of typical stream erosion form. It is certain also in this case, if glacial overdeepening is admitted, that there can be no stream notch in the bottom of it. The significance of this lies in the probability that the floor is approximately the same level on a considerable portion of the bottom, so that when once the margin of this floor is touched the gorge as a whole is thereby determined for depth.

After plotting the borings data and relying upon the factors that seem to be most firmly established, it appears that the following statements are as definite as the facts will warrant:

a The average slope of the Storm King side of the valley above river level is nearly 38°, and this is in several steps or sections of steeper and flatter slopes. The Breakneck side is about the same.

b The average slope of the Breakneck side of the gorge below present water level (the side on which alone there are enough data to plot a fairly good curve) does not vary much from this same value [*see* accompanying profile]. And it is also in steeper and gentler slopes, apparently a series of U-shaped forms set one inside the other, each inner one deeper than the next outer one. Each successive inner step is approximately 300 feet deeper than the last and 1000 feet narrower.

It is certain that this sort of profile is not as simple as at first appears. The surprising feature is the close approximation of the slopes above and below present river level. In view of the fact that glacial widening has been practically proven, as shown before, not much importance can be attached to this uniformity or similarity of slope. Ordinarily such a persistence of slope would be taken to indicate simple stream origin, but having abandoned that hypothesis, the value of the angle as a factor in estimating probable total depth is lost. In short, one can not assume that the deepest point is indicated by the intersection of the slopes of the two sides.

But there is one feature that is at least suggestive. That is the uniformity of the succession of steps and slopes. It was noted above that each successive inner one is about 300 feet deeper and 1000 feet narrower. If this uniformity and proportion is main-

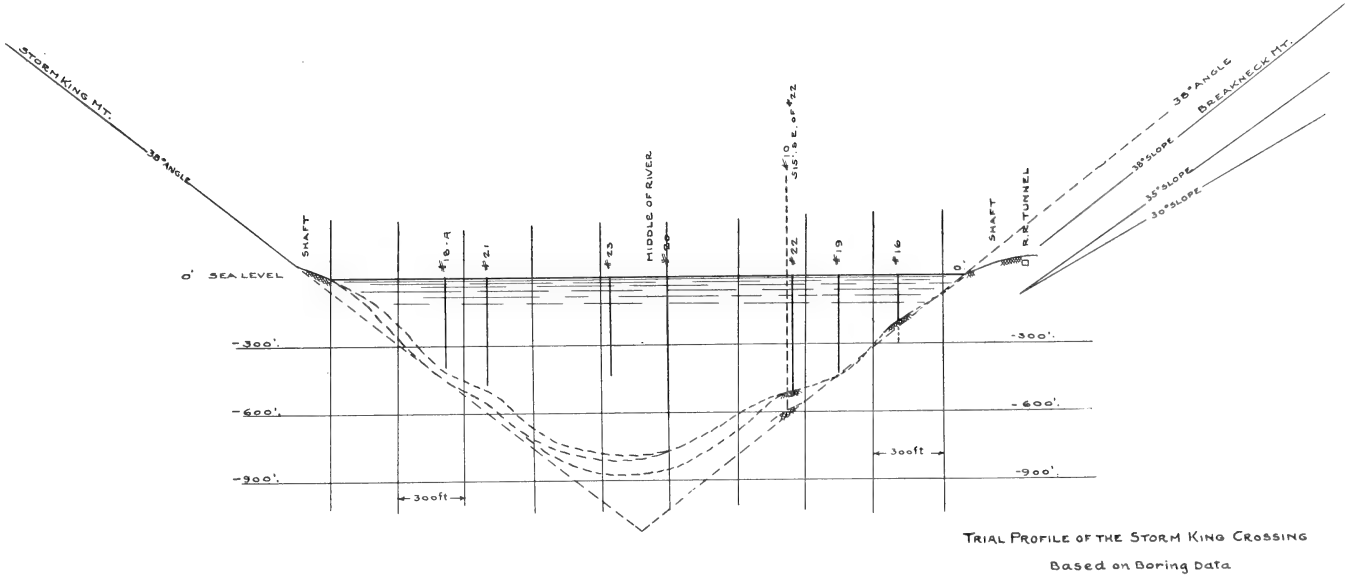


Fig. 14 A study of the Hudson gorge profile showing location and depths of the principal borings. The tendency to U-shaped forms, one within the other, is believed to be indicated by the borings on the Breakneck mountain side and give a suggestion of the probable depth of the innermost form.

tained for the next inner one — inside of holes no. 10 and no. 22 — there would be room for only one more and its approximate depth would lie somewhere between 800 feet and 900 feet below tide.

Recent drilling has shown a marked difference between holes no. 10 and no. 22. Hole no. 10 located 500 feet southeast of no. 22 is nearly 100 feet deeper. Since no. 10 is nearly straight down stream this discrepancy is disturbing. But if one considers the distance of each from the east bank it is noted that no. 10 is 900 feet out and no. 22 is 800 feet. Hole no. 10 is thus about 100 feet nearer the middle of the stream and allowing for this additional distance according to the profile as known it ought to be at least 70 feet deeper than no. 22. This corrected difference then of 30 feet does not seem to be of much importance.

Summary. Everywhere in its lower course the Hudson exhibits the character of a narrow gorge, sometimes of a gorge within a gorge, most of which is either submerged or buried several hundred feet.

Depths of 200 to 300 feet are average and for the last 60 miles of its course represent widths of 1000 to 3000 feet.

Greater depths are believed to be maintained continuously within a narrower inner notch, but of this there is no conclusive proof and very little evidence outside of a few Storm King borings.

The Storm King-Breakneck notch is over 751 feet deep. But it is abnormal at least in width and probably also in depth, due to ice erosion.

The conditions indicate (*a*) rapid stream erosion while the continent stood much higher than now, (*b*) glaciation which enlarged the gorge in at least a few places and filled it with rock debris and later with mud during submergence, (*c*) finally an emergence with minor oscillations and erosion to the present time.

4 Origin of the present course of the Hudson

The course of the Hudson is in most respects no more abnormal than that of the Susquehanna. Both flow across mountain ridges in such manner as to indicate their superimposed character. Both date back to the Cretaceous peneplain. But the striking feature of the Hudson is its straight course. As Hobbs and others have pointed out, the river is abnormally straight for more than 200 miles — and this in spite of the fact that it crosses the bedding and other structures of the country rock at nearly all points at an

oblique angle. Such conditions are especially notable south of the Highlands where the Hudson cuts at a low angle across the ends of a succession of complex folds of the crystalline metamorphics for 30 miles to New York city. But this is true only of the east side of the river. The west bank is an almost unbroken uniform escarpment of the Palisade diabase intruded sheet underlain by Newark sandstones, which if laid down upon a pretty well planed Pretriassic surface might easily control the Hudson, and which would not differ from its present course.

The most evident exception to this is the course of the river from Hoboken to Staten Island. Instead of following the line of contact between the crystallines and Triassic formations, the river cuts through the crystallines leaving large masses of serpentine and associated schist on the west side. This together with the behavior of the river in cutting across the strike farther north near the Highlands is believed to strongly favor the fault theory of location especially south of the Highlands. The same conditions would be favorable to the development of a narrow gorge and perhaps a very deep one rapidly eroded along the crush zone of the fault.

From the northern entrance to the Highlands to Haverstraw bay, where the Palisades are reached, the stream course is not by any means straight, but shifts from longitudinal structure to cross structure alternately in a zigzag manner. North of the Highlands the course is more direct again. On the whole the present explorations have added little to the facts bearing upon this question. Faults crossing the river are common and easily recognized. Occasionally one appears to pass into the river gorge at a very small angle and not reappear. In a few places, especially in the Highlands, the course does not seem to be consistent with the hypothesis of a large fault line. It is to be expected that further work at the Hudson river crossing will add materially to the facts relating to the structures within the gorge.

CHAPTER III

GEOLOGICAL CONDITIONS AFFECTING THE HUDSON RIVER CROSSING

General statement

This is essentially a study of the geologic features and conditions shown by exploration to have an important influence upon the choice of river crossing for the aqueduct. In the beginning it was possible to consider that any point between Poughkeepsie and New York might furnish a crossing. The early preliminary investigations showed that it would be desirable to cross either above or within the Highlands and subsequent exploratory work throws light on different possible locations in these regions. Fourteen different lines were tested by wash borings. Later some of these were tested by diamond drill. As data accumulated it was possible to eliminate many of the trial lines and the more detailed and critical studies became confined to a few important possible crossings.

In making a comparison of them as to geological environment it is evident that they fall into two distinct groups[1] [*see* fig. 15]. One, that may be designated the "New Hamburg" group is represented by the "Peggs point," "New Hamburg," and "Danskammer" lines and is characterized by a series of much folded, faulted and crushed sedimentary rocks, chiefly slates, limestones and quartzites. The other, that may be called the Highlands group, is represented by the "Storm King," "Little Stony point," and the "Arden point" lines and is characterized by crystalline metamorphic and igneous rock of a much older series.

A judgment as to the most desirable crossing involves the selection of one of these groups chiefly upon general geologic features, and finally a selection of a particular line upon minor differences of materials or structure.

In the first place it seems necessary to consider, for each group,

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[1] There have been other suggestions for crossing the Hudson river, farther upstream and farther down than these — one being at New York city — but none have had sufficient claim to attention to encourage much detailed work or so careful consideration as those here discussed.

A shift of position of the Hudson river crossing involved a corresponding shift of a large section of the northern aqueduct line. The first choice of location occasioned a shift southward of all that portion between Ashokan reservoir and the Hudson.

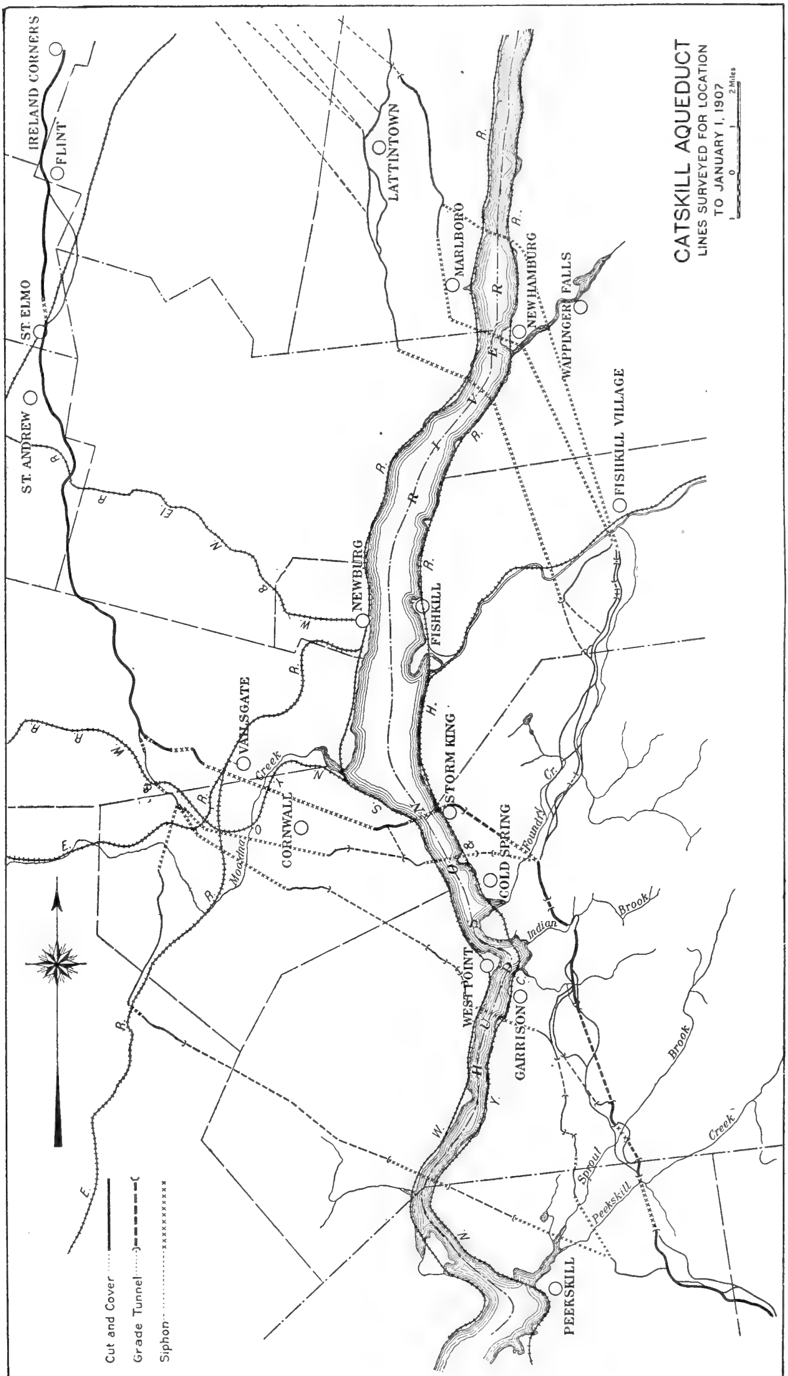

Fig. 15 Outline map showing alternative lines studied as possible crossings of the Hudson river

the whole length of pressure tunnels whose position would be modified by a shifting of river crossing. This is because the aqueduct will approach the Hudson with nearly 400 feet head — i. e. 400 feet above river level or with an equivalent pressure. For this reason it is considered necessary to plan a rock pressure tunnel beneath the river which can deliver the water at nearly the same elevation again on the east side.

Thus any one of the "New Hamburg group" involves a continuous pressure tunnnel reaching from the margin of Marlboro mountain to Fishkill range, a distance of approximately seven miles, while any of the "Highlands group" permits the substitution of two more or less separate siphon tunnels (Moodna creek and Hudson river) of considerably less combined total length.

A reliable conclusion as to the choice of crossing is probably best reached through a comprehensive understanding of the geologic development of the region together with a consideration of specific local conditions. With this end in view a condensed outline of geologic history, so far as it bears upon the questions at issue, is inserted. But for a more comprehensive discussion of these matters the reader is referred to the explanatory chapter of part 1.

Geology

This particular locality, including as it does the Highlands of the Hudson and the district lying along its northern border, is one of the most complicated stratigraphically and structurally to be found in the entire region. The strata represented include more than half the total geologic scale reaching from the oldest sediments following the Archean up to and including a part of the Devonic series [*see* pt 1]. The rock types include granites, diorites, gneisses, schists, marbles, serpentines, slates, quartzites, sandstones, limestones, shales, and, less extensively, other varieties. And the region bears the evidence of no less than three periods of mountain-making disturbances, each in its turn adding to the succession of foldings, faultings and unconformities.

The oldest formation is a crystalline gneiss — a characteristic rock of the Highlands. It represents an ancient sediment that has been completely recrystallized during some of the earlier mountain-making period. It is older than the Cambric. Interbedded with it to a limited extent are quartzite beds, ancient limestones (now usually serpentinous in character) and schistose beds; and in it are many igneous injections, mostly granites of various types. All

these igneous injections are therefore younger than the gneiss and are very large and abundant in certain cases. The granite of Storm King, Crows Nest and Breakneck ridge belongs to this type.

Following the sedimentary cycle represented by the above series, and perhaps others not now preserved, the region was folded into a mountain range, the series was extensively metamorphosed and passed through a long period of erosion during which it was again reduced to sea level position and began to accumulate a new series of sediments.

The lowest beds occurring upon this foundation are sandstones, now changed into quartzite. In places they are conglomeritic, and may now be seen projecting into the valleys along the Highland border. This formation is of Cambric age, and is from 200 to 600 feet thick in favored places. It forms an almost continuous belt along the north side of the Highlands except where cut out by faulting, and extends with similar breaks beneath the later sediments northward. This quartzite is known as the " Poughquag."

Upon the quartzite of this series there was developed a succession of limestone beds at least 900 to 1000 feet in thickness. This formation is known as the " Wappinger " and includes some beds that are of Cambric but for the most part of Ordovicic age.

The final member of this series is a shale and shaly sandstone in places changed to slate. It is quite variable in actual character and has a great thickness, never yet successfully estimated, but probably several thousand feet. This is the so called " Hudson River slate " series. In this region they are of Ordovicic age.

This is the succession which the proposed Hudson river lines has to penetrate in a pressure tunnel. Later Siluric and Devonic strata lie in the immediate vicinity of this alternative line, but add no complication to the problem as it now stands. Therefore no other formations need be considered except the glacial drift. This covers almost every rock surface and is deeply accumulated in some places, notably in the narrow gorges and valleys, obscuring the finer original topographic lines.

A summary of the history of the formations chiefly involved in this problem with a suggestion of later erosion activities may be tabulated as follows:

Cenozoic	Glaciation Reelevation Erosion (interrupted) Elevation (rejuvenation)

Mesozoic		Erosion to peneplain ....Unconformity A long interval including two mountain-making epochs and at least one period of general sedimentation
Paleozoic	Ordovicic	Hudson River slates Wappinger limestone
	Cambric	Poughquag quartzite
		..................Unconformity A long interval including mountain folding, igneous injection, erosion, and perhaps other sedimentations
Proterozoic		The metamorphosed schists, limestones, quartzites etc., together with accompanying intruded igneous masses — forming the basal gneisses of the Highlands

The evidence of such succession and history gathered from the scattered outcrops of rock in the immediate area, is nowhere better shown than in the field covered by this investigation.

Structure

When such outcrops as are known are plotted and organized, several important facts become clear.

1 The folds run with remarkable persistence northeast and southwest.

2 The succession in many places is not normal. Often a whole formation or even two of them are missing and formations that should be separated are brought side by side. Faulting therefore is prevalent and the occurrences show that these large fault lines usually run northeast and southwest.

3 A consideration of the dips of the strata shows that most of the folds are overturned as if pushed by some general movement from the southeast.

4 This same movement causes the faulting to be largely of the overthrust type, and in some cases the lateral displacement attained in this way may possibly be several thousand feet.

5 Isolated "islands" of the older rock formation appear out in the later sedimentary area. They all seem to belong to prolongation of the ranges of the Highlands and their abundance undoubt-

edly complicates the underground structure throughout a considerable belt.

6 The Highlands area terminates in a serrate margin which, in the latest thrust movements from the southeast, must have created very unequal distribution of stresses within the slate-limestone region to the north causing additional cross folding and faulting. For the most part these can be traced only a short distance before losing their identity.

In a mountain folding movement, the uppermost rocks are most broken and displaced or crushed while those of greater depth may be bent or uniformly folded or even recrystallized. It would appear that this latter was the condition of the Highlands rock series during its earlier history. And even in the latest movements its lines appear to be less radically disturbed than the slates and limestones to the north. Most of the disturbances that invite serious consideration belong to the latest period of these mountain-making upheavals.

Comparison of routes

1 **New Hamburg group.** This group of crossings is in the later sedimentary series. Hudson River slates and Wappinger limestone are the chief formations. But within the southern third of the tunnel, at least, the underlying Cambric quartzite and the older Highland gneiss would be cut — the quartzite possibly three times. The succession therefore will be of considerable complexity as a whole.

All of the formations involved are thrown into very steep dips at most places and are consequently liable to rapid and unexpected changes — some of which probably do not show at the surface.

There are several fault lines belonging to the major northeast and southwest series to be crossed by such a tunnel — one of them in each case being met at considerable depth and beneath or adjacent to the river. These faults besides being the weakest zones of rock as a rule, are in addition the most unstable in any possible future earth movements. Although there is no evidence of recent displacement along these lines, still such a thing is always possible and recent serious effects of this kind on the Pacific coast suggest caution. It is manifestly advisable, if possible, from every standpoint to avoid crossing several of them.

In the field there are numerous springs of very large flow along many of the limestone borders. The concentration of them to these situations in addition to the occurrence of an occasional sink-

hole, leads to the conclusion that they are more intimately dependent upon the limestone structure for their existence than upon the glacial drift or any superficial factor. Their abundant flow, sometimes on high ground, indicates rather extensive structural connections and this is believed to be the limestone bed itself and that such flows would be encountered also in depth. The occurrence of sinkholes suggest also possible solution channels and cavities and distant outlets. The types of rock to be encountered on the lines represented by this group are easily workable. Among them all the Hudson River slates is probably the most satisfactory from any standpoint. It is generally easy to penetrate and has a capacity for healing its own fractures. For this reason it can be considered good ground, tight and safe. But a considerable distance of the tunnel can not be kept in slate — perhaps even more of it than can be proven from surface observations. The other formations are considerably less satisfactory. The limestones are in places shattered and are liable to abundant flow of water. The quartzite is extremely hard, as difficult to penetrate as granite, and where crossed by the faults is probably not healed at all, while the gneiss is doubtless of similar character to that of the Highlands crossings to be discussed later.

Only minor modifications result from a choice of the individual crossing, whether " Peggs point," " New Hamburg," or " Danskammer." In one of them, New Hamburg, it would appear possible to cross the actual river section wholly in slates. This seems to be the reasonable conclusion from the diamond drill boring at Cedar Cliff. But even that line necessitates crossing at least two fault contact lines immediately at the east bank and beneath Wappinger creek at depths not immensely less than that below the river itself and both wholly within the range of influence of the river waters. It would appear therefore that the situation is not materially altered in the present discussion, no matter which particular crossing of this group is considered.

2 **The Highlands group** [*see* cross section]. In this group of crossings there are two separate features to consider. (*a*) the Moodna creek valley which these lines all cross, and (*b*) the Hudson river itself. Their characteristics are as follows:

a Moodna creek [*see* separate Moodna creek discussion]. So far as known Moodna creek can be crossed almost wholly in slate. It is possible that the underlying limestone may come near enough to the rock floor of the valley to be penetrated but there is little

direct evidence of it. The ancient valley is deep and probably marks a line of displacements which can not be avoided, no matter what route is chosen. The fault contact at the border of the Highlands is not expected to prove troublesome as it seems very tight at the exposures seen. The buried granite ridge (a continuation of Snake hill) which underlies the western end is now known to come within the limits of the tunnel and adds one more complication.

Except for the fact that the ancient Moodna valley is deep and filled with heavy drift that is unusually difficult to prospect, there would seem to be no source of special trouble. It has no lines of weakness that are not also present in the more northerly districts and the tunnel has chances of crossing them under more advantageous conditions without so much complication with the limestone series as characterizes the New Hamburg group.

b Hudson river. Among the Highlands group of crossings there is considerable difference of structure dependent upon the exact location of the crossing. The conditions that prevail may be summarized as follows:

(1) **Storm King location.** This is wholly in massive and gneissoid granite. The rock is the most massive and substantial body of uniform type found in the Highlands. The course of the river indicates some weakness in that direction. This weakness may be some minor crushed zone or even the jointing alone that prevails throughout the exposed cliffs. But there is no direct evidence of faulting, cutting the line and such crushing as may be encountered is believed to have originated at such depth and under such conditions as to cause no large disturbance. The freedom of this formation from all bedding structures and natural courses of underground water circulation on a large scale is an additional factor. There is absolutely no other place, within the region, where the Hudson river can be crossed from grade to grade in good ground of a single type with so great probability of avoiding all large lines of displacement.

(2) **Little Stony point location.** The conditions that prevail at this point are similar to those that characterize the Storm King line. The only known difference is in the considerably more shattered condition of the granite, especially on the west shore at Crows Nest. It is estimated that this crossing is less favorable by reason of just this poorer condition of the rock and the somewhat greater yielding to regional disturbances that it seems to indicate.

(3) **Arden point or West Point location.** On this line the river would be crossed in the gneiss series proper instead of in granite.

Plate 16

The Storm King — Breakneck mountain gateway to the Highlands as seen looking north from West Point. Two of the proposed crossings lie in this gap — the Storm King line reaching to Breakneck, the rugged mountain on the east side, and the Little Stony Point line which crosses from Crows Nest on the west to Little Stony Point, the small low point on the east side. (Photograph by Board of Water Supply)

It is largely an ancient stratified series much metamorphosed containing belts of interbedded limestones, quartzites, and schists, in addition to the more substantial feldspathic gneiss. The eastern bank of the river bears also abundant evidence of extensive crushing and shearing and is believed to indicate a displacement in this zone. For these reasons the West Point crossing is considered an unfavorable route compared to either of the others of the Highlands group.

Summary. In a comparison of the geologic features that are of most importance in contrasting the possible routes for the Hudson river crossing the following points are considered of most importance.

1 The New Hamburg group of crossings involves (*a*) the longest tunnel, (*b*) the more complicated structures, (*c*) the greatest number of known faults, crush zones, and related disturbances, (*d*) the more variable series of rock types to be penetrated, (*e*) the greater tendency to encounter heavy underground water circulation, (*f*) the greater probable susceptibility to disturbance from future earth movements, and (*g*) the greater number of uncertainties of rock relations.

2 In contrast the Highlands group admits of (*a*) shorter total tunnel length, (*b*) the most profound fault lines of the district are crossed either in high ground or are avoided or, because of the rocks involved, promise the least possible trouble, (*c*) the Hudson river itself can be crossed in a single formation with probability of avoiding lines of largest structural weakness confining the greatest pressures and deepest tunnel work within the most uniform and substantial rock of the whole region.

There are, of course, many unknown or only partially known features obscured beneath the covering of drift or lying beneath the river itself; but, however many there may be, it is not believed that they can materially change the general situation. The major characteristics are so well marked that any addition to those already known would in all probability increase the difficulties of the New Hamburg group of routes at least as much as and perhaps more than those of the Highlands group.

In view of the above facts and inferences the judgment has been in favor of the Highlands group of crossings as the more defensible on geologic grounds as a route for the aqueduct line. Furthermore, in accord with the preferences already noted, the Storm King location is regarded as the most likely to give satisfactory results.

Quality and condition of rock

The rock of Storm King mountain and of Breakneck ridge at the Hudson river crossing is a very hard granite with a gneissoid structure of variable prominence. The color varies from grayish to light reddish and the structure is always coarse passing into pegmatite facies that occur as stringers or irregular veinlets. The grayish facies is of slightly finer grain and more gneissoid. Those portions that have been sheared are still darker. There are many joints at the surface running at various angles and an occasional slickensided surface. The mass is cut by several dikes of more basic rock (diorite) of widths varying from a few inches to 8 feet. These dikes are somewhat more closely jointed than the granite and consequently a little more readily attacked by the weather. But where protected they are equally substantial for underground work.

The chief variation from this condition is where crushing or shearing has induced metamorphic changes. Wherever bed rock has been reached at this point and to such depths as workings have penetrated the rock is of this type.

The work includes (*a*) four inclined drill holes from the river margin — two starting from the surface and two from chambers set off from shafts at a starting depth of about 200 feet, (*b*) several vertical holes in the river itself, and (*c*) two large working shafts 20 x 20, one on either side of the river.

These give all the data[1] known as to the condition at depth. From them it is apparent that crushing and shearing have been prominent. Many splendid specimens of crush breccia are thrown on the shaft dump. But its present condition at the depth involved is sound and durable. The fractures are rehealed. There has been a recombination of constituents giving a new matrix of complex silicates among which epidote is the most characteristic, while simple decay is of little consequence. For strength and permanence the conditions could not well be improved. There is no reason to apprehend any change for the worse for the reason that the same tendencies must prevail at that depth throughout. It would appear therefore that faulting movements, or the existence of a fault zone of importance can not become a serious obstruction, because of the tendency to

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[1] Since this paragraph was written four inclined diamond drill borings have been made from chambers at depths of about 200 feet in the shafts. These have now penetrated the whole distance beneath the Hudson with very satisfactory results.

Plate 17

Storm King mountain and the Hudson river from Breakneck mountain showing the location of the proposed pressure tunnel by the line of drill rigs engaged in exploratory boring. (Photograph taken November 26, 1907. Board of Water Supply)

heal up the fractures and so make the rock about as substantial as before.

It is noted elsewhere that faulting is common in this region, and that in a considerable portion of its lower course the Hudson probably follows such structures. It is, however, wholly unnecessary to assume that its whole course is a fault line. Whether or not there is a longitudinal fault zone of any prominence in the river at Storm King is unknown. There are several cross faults, both above and below this point, that give much clearer surface evidence of their presence. Fault zones have proven to be objectionable ground in many places along the aqueduct line, but elsewhere the data refer chiefly to situations favoring more ready underground circulation, i. e. at higher levels. In this particular case the rock in question lies below former ground water level within the belt of cementation rather than up in the belt of decay, and there is probably no disintegrated rock from any cause.

CHAPTER IV

GEOLOGICAL FEATURES INVOLVED IN SELECTION OF SITE FOR THE ASHOKAN DAM

Topographic features of the southeastern margin of the Catskills, where the chief water supply is available, fixes the approximate location and bounds of the principal reservoir. The accompanying map, a portion of the western part of Rosendale quadrangle, shows the situation. The part of the work involving the chief geological problem was the choice of the principal dam sites on the Esopus. This is known as the Ashokan dam. This part of the Catskill system belongs to the Reservoir Department under Mr Carlton E. Davis as department engineer.

There were originally considered three sites: (1) at "Broadhead bridge," (2) at "Olive Bridge," (3) at "Cathedral gorge" or the "Tongore" site. Any one of these seemed possible from a topographic standpoint. Later developments in regard to storage capacity and engineering considerations finally reduced the practicable sites to two — the "Olive Bridge" and the "Tongore." These were then explored thoroughly as an aid to determining whether or not there were favorable or unfavorable conditions at either location. Trenches were dug, shafts were sunk, wash holes were put down, and drill borings were made. The amount of such work done was sufficient to show the actual conditions both of the drift and bed rock and incidentally to throw some light on minor matters in geologic history.

This discussion is essentially a summary of these data and a comparison of the geologic conditions indicated by the explorations[1] of these two sites and a statement of some of the geologic characteristics of the area.

1 General geologic conditions as shown by the explorations

Bed rock is dark colored Devonic sandstone and shale, the Sherburne formation, lying almost horizontal, strongly jointed, plainly bedded, and of good quality for the foundation of the dam.

At both locations the present Esopus flows in a postglacial gorge

[1] In this work of exploration a very efficient staff of engineers was engaged. Among those having very much to do with the features here discussed are Thaddeus Merriman, division engineer, J. S. Langthorn, division engineer and Sidney Clapp, assistant engineer.

and there is a somewhat deeper buried channel a short distance to the north side. In each case this old channel bed rock is probably less fresh and substantial, due to former weathering, than the present exposed surfaces.

In each case glacial deposits reach a thickness of more than 200 feet within the narrow valley or gorge, especially along the north valley wall within the limits of the proposed dam.

Special geological conditions. The factors in which there is most variation and which are of most significance in a comparative study are those belonging to the glacial drift deposits. In order to properly estimate the influence of some of these features it will be necessary to briefly consider the types of material represented at different places and the conditions under which they were formed.

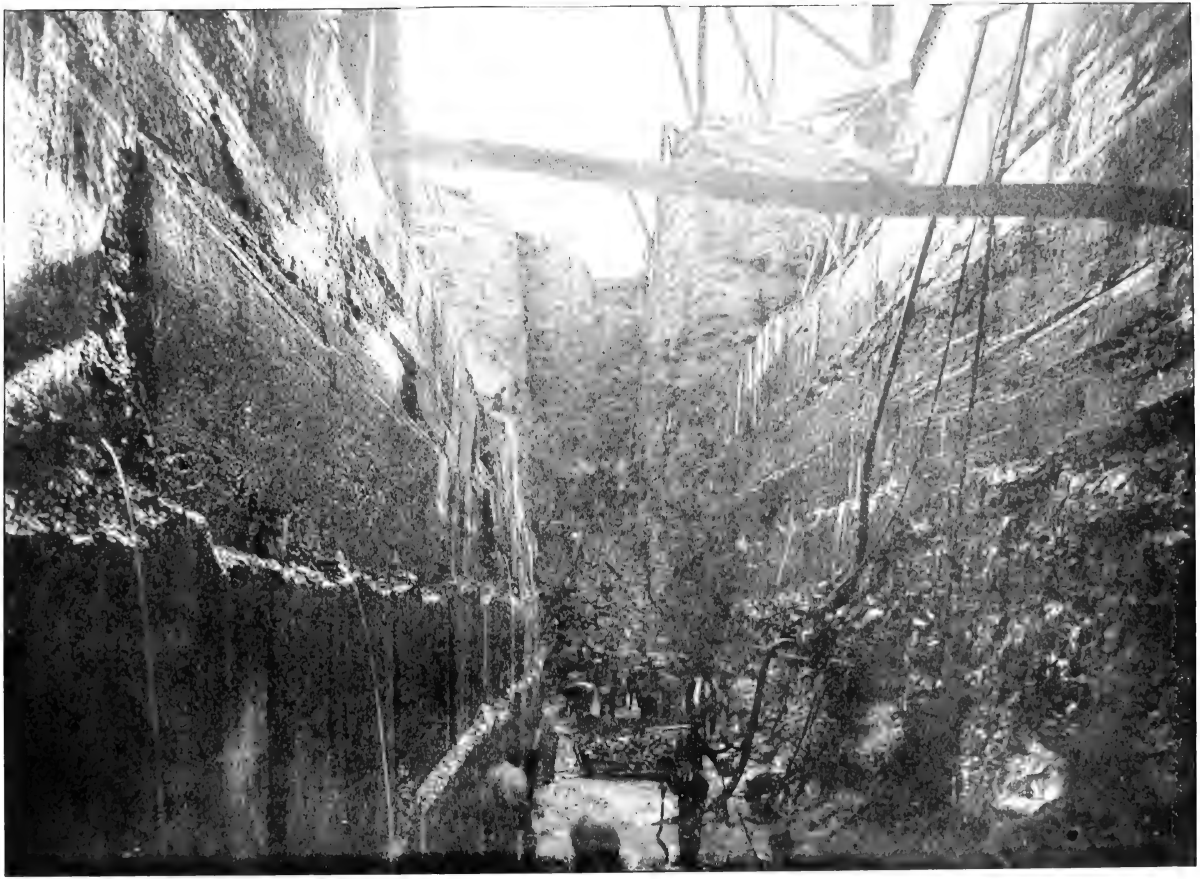
Types of material. *Till.* Heavy bouldery till, mixed clay, sand, gravel, and boulders, is the most abundant type of material. It forms especially the chief surface material throughout the region, and is the surface type at both sites. It becomes at places quite sandy, but is almost everywhere good, impervious material because of its mixed character.

Laminated till. At a few places, notably in the Beaver kill near its mouth, and in a trench above Olive Bridge, and in the "big dugway" above West Shokan, strong lamination appears in heavy stony till as if laid down rapidly in comparatively quiet water such as the margin of a lake. This material is especially impervious.

Gravel hillocks. A few small hillocks with morainic contour, indicating a dumping ground for some glacier on a small scale, occupy the flat immediately west of Browns Station. They were, at a very late stage, piled into the course of a former glacial stream whose delta deposits occupy the sandy bench above the 500 foot contour just north of Olive Bridge.

Assorted gravel and sand. This material is abundantly developed just north of Olive Bridge. It seems to have formed a delta deposit at the mouth of a glacial stream that emptied into the main valley at this point. The running water washed almost all of the clay and extremely fine material farther out, where they settled in the bottom of a small glacial lake that was at that time held in this upper portion of the Esopus valley. The dam that held in this body of water which reached above the 520 foot line stood near the proposed "Olive Bridge" dam site. The materials forming the dam were in part the glacial till that is now found on that site and

Plate 18



Cut-off trench in the Sherburne sandstones and shales at Olive Bridge dam (Ashokan). (Photograph by Board of Water Supply)

in part the ice itself, which came in from the northeast, helping to complete the barrier. Into this lake the streams from the melting ice margins deposited their load of silt. This is well shown in the trenches cut across the terrace ¾ of a mile above Olive Bridge.

A similar occurrence is seen at the cemetery near West Shokan.

Laminated sand and clay. In all cases where silts were carried into the lake basin the finest materials were carried in suspension to greater distances from the margins, and slowly settled out in the form of alternate laminae of clay and fine sand. Each sandy layer represents a fresh supply of material and rapid precipitation of the comparatively heavy grains; while each clay layer represents a period of greater quiet or decreased supply during which the finest particles settled to the bottom. A predominance of fine sand indicates either abnormal supply or proximity to the supply margin, while a predominance of clay represents either uniform and moderate supply or greater distance from the supply margin.

These deposits are nearly impervious to water moving vertically, but much more pervious laterally and especially so in the most sandy portions forming the marginal facies.

This type of deposit is to be seen at the surface at about the 700 foot contour 2 miles north of Shokan, above the "big dugway," also in the trenches cut into the terrace at about the 500 foot contours ¾ of a mile north of Olive Bridge, and it is probable that this same type underlies the northern half of the "Tongore" site. The material marked "fine sand" at and below the 400 foot line on the accompanying "geologic section" *G-H* is judged to be of this type.

Pebbly clays. These are developed to only limited extent and indicate probably floating ice in addition to the other methods of distribution.

Gravel streaks and assorted pebble beds. Wherever water flowed with considerable current across the material either before or after deposition the finer particles were removed and only gravel and pebbles, too heavy to transport, were left behind. Some of these gravel beds were developed in the intervals of successive advances and retreat of the ice when for a time the lower valleys were unoccupied. In many places the succeeding advance of the ice would plow all these surface materials up again and mix them into the usual till; but occasionally the oncoming glacier simply covered these deposits with its own till mantle, and they are preserved as records of these minor interglacial stages. Such behavior would be

more likely to occur in the deeper channels. To this class of deposit belong some of the gravel beds of the "Tongore" site, notably that shown in one of the deep shafts. It is probable that the zones where the wash rig experienced a "loss of water" are most of them of this type.

2 Summary of geologic history

In preglacial time the Esopus valley was occupied by a stream of similar capacity to the present Esopus creek. Its channel lay to the north side of the narrow valley, having adjusted itself in conformity to the slight dips of the Hamilton sandstones and its principal joints. At the points under investigation this original channel is buried under several kinds of glacial deposits whose source of accumulation was chiefly from the north and northeast, blocking the stream channel and forcing the stream to the opposite (south) side. The direction of movement was favorable to the damming of the Esopus creek valley and the deposits indicate that this occurred at several different times and at different elevations and that corresponding lake conditions occasionally prevailed. It is equally clear that there were intervals of retreat of the ice with attendant stream action and the development of gravel beds, followed by another ice advance, either obliterating the surface features or covering the previous deposits with another till layer. With each successive withdrawal the local streams found themselves more or less completely out of place, and consequently their characteristic deposits formed in these intervals may be found in unlooked for places wholly inconsistent with present surface contour.

At the final withdrawal of the ice, Esopus creek found itself entrenched along the southern margin of the valley and has cut a postglacial rock gorge instead of removing the compact till from the original channel. But wherever only modified drift, either sand or clay, was the valley filling it scooped out great bends so that a large proportion of this type has been removed from the valley, and only the margins remain as terraces or covered beneath other protecting deposits.

3 Application to the choice of dam site

a **"Olive Bridge" site.** The trenches and shafts together with surface exposures indicate that the glacial drift at the Olive

Plate 19

View across the Esopus valley to "Millwheel Gap." In a portion of this glacial lake basin modified sands and clays were deposited while an ice barrier closed the outlet of the valley. The "Gap," the sharp notch in the lower slope of the mountain, is interpreted by Darton as the outlet or overflow for the surplus waters during that stage. (Photograph by Mr J. E. Hyde of Columbia University)

Bridge site, at one stage in the glacial history, served as a natural dam and that water was successfully held above it to an elevation of 530 feet and perhaps more.

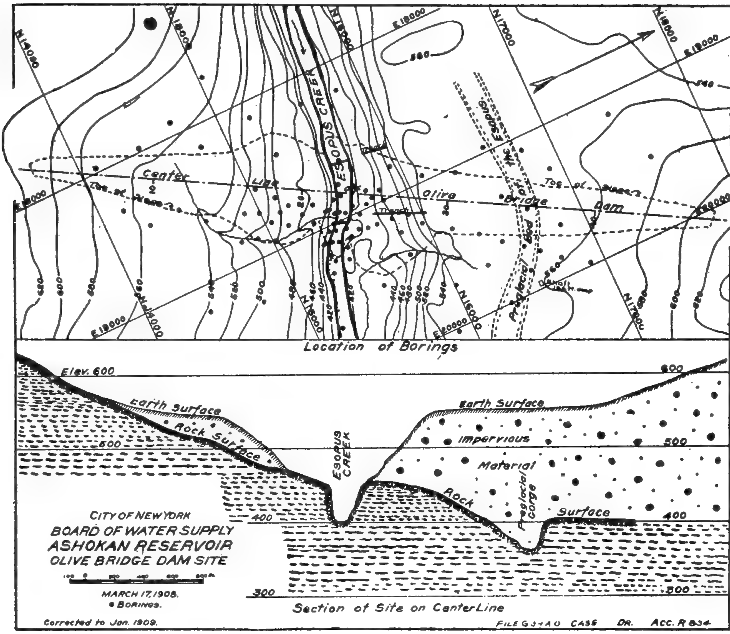


Fig 16 Location of the Ashokan dam at Olive Bridge site and a geologic cross section. The small dots in the plan indicate exploratory borings. The section shows the rock profile indicating a preglacial channel of the Esopus. The present Esopus flows in a new postglacial channel at a higher elevation.

The lowest materials in contact with bed rock are heavy stony till, laminated till and stony laminated clays — all good impervious material wherever exposed and tight upon bed rock. Sands and laminated clays are extensively developed immediately northward of the site and streaks of these deposits interlock to a limited extent with the till materials of the site itself, but they do not extend far and die out in wedges among the heavy deposits that characterize the southern slopes of the hill forming the northern terminus of the dam. These pervious streaks do not extend at any point continuously through this hill and consequently as a whole the present barrier as it stands is practically impervious. The poorer materials (assorted gravels and sands) characterize the upstream side, and the better, more impervious materials (till and laminated boulder clays) characterize the downstream side of the proposed Olive

Bridge site. It is therefore advisable to locate any such structure as a dam at a point as far down stream on this site as other engineering factors permit.

b "**Tongore**" **site.** At Tongore, bed rock is at least a hundred feet deeper than at Olive Bridge. In the deeper parts, below the 400 foot line the deposits as indicated by the wash borings [*see* sections] are interpreted as a fairly continuous succession of till, stratified sands and gravels, and laminated sands and clays belonging to two or three different stages of accumulation. Upon this the heavy upper till was laid down. It is believed that the records fully support this view and that the stratified or laminated materials were accumulated at a time when a temporary dam existed at some point still farther down the Esopus valley. It is apparent furthermore that the most porous zone is at the junction of the upper till and the lower stratified deposits and in part is represented by the assorted pebbles of stream wash — in general not far from the 400 foot line. These middle zone deposits are believed to extend continuously through the drift ridge that forms the northern half of this site. As before noted, though rather impervious vertically,

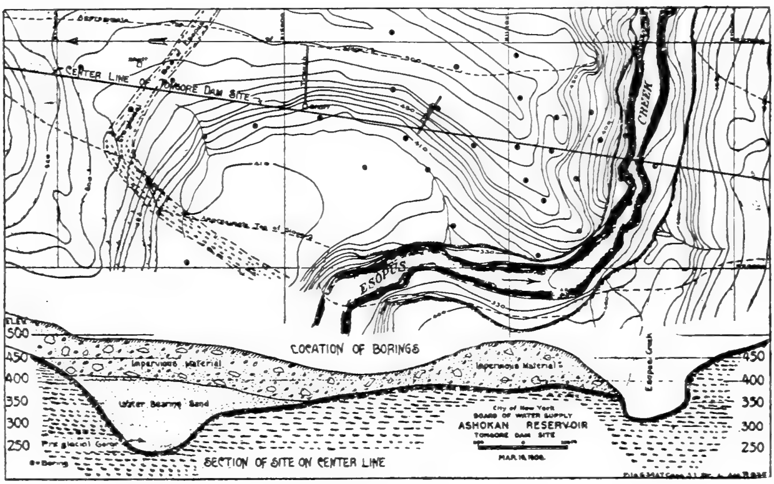
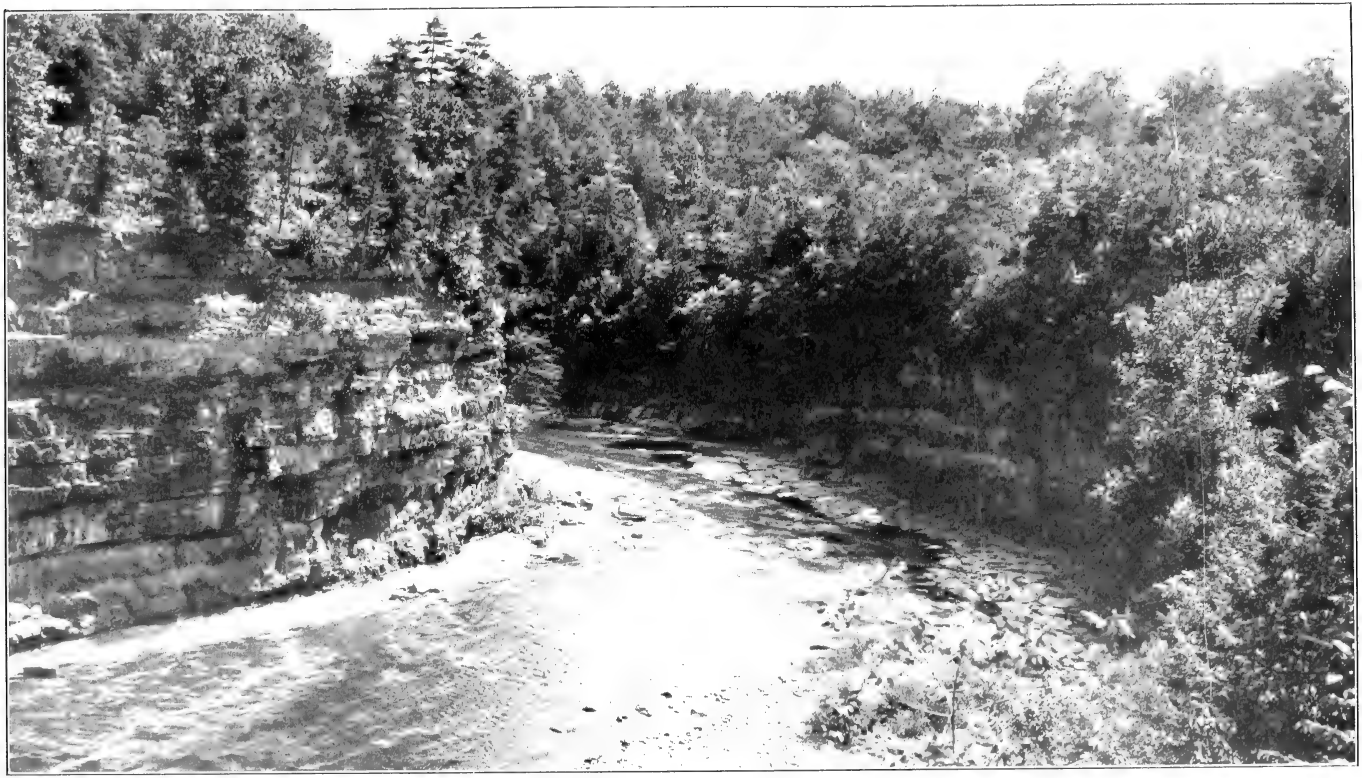


Fig. 17 Plan and geologic section at the Tongore site. The dots on the map indicate exploratory borings and the course of the buried channel of the preglacial Esopus creek is shown making a right angle bend to the north. The section shows the buried channel, the new postglacial channel and the great accumulation of porous modified drift which is regarded as one important objection to this site for the dam.

some of these deposits allow ready lateral movement of water. This is held to account for the rather persistent occurrence of springs or seepage along the creek bank at about this level both above and



Cathedral gorge, a postglacial entrenchment of Esopus creek at the Tongore site. The preglacial gorge lies at the north side of the valley buried beneath 250 feet of drift. (Photograph by Board of Water Supply)

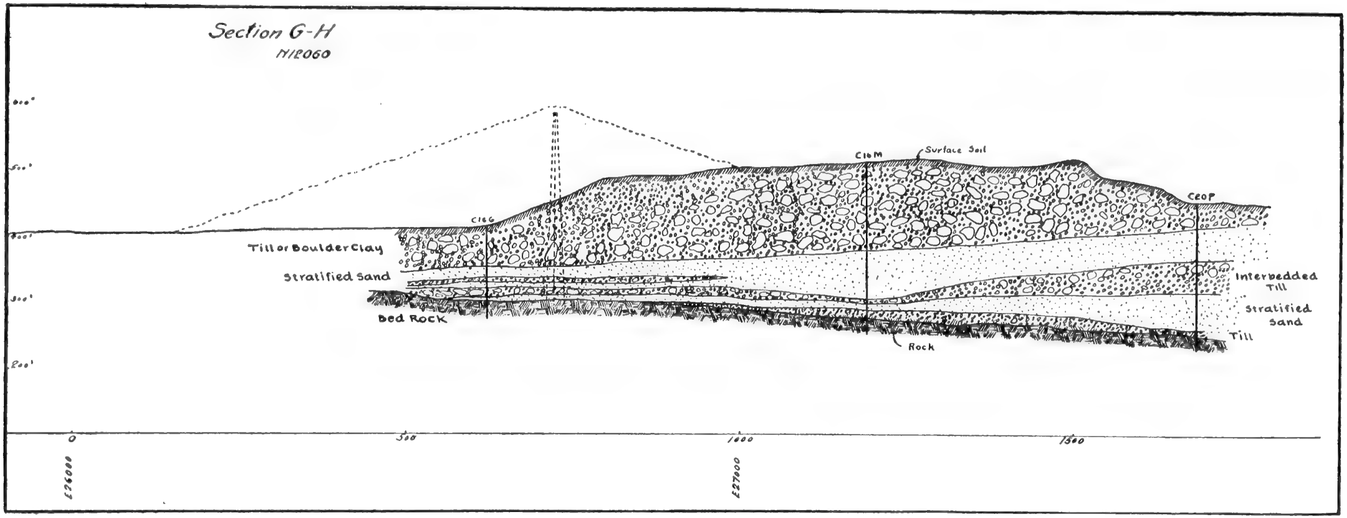


Fig. 18 Detail of drift character at the Tongore site showing extensive and continuous stratified sands characterizing this location, which, because of their perviousness, represent poorer geologic conditions than were found at the rival Olive Bridge site.

below the site. The great thickness of these laminated beds, in places a hundred feet or more, together with the abundance of sand in them, and the caving tendencies exhibited by them in one of the large shafts, indicates poor conditions for such a piece of work.

The behavior of one of the test shafts throws some light on conditions within the drift deposits. At this place after sinking into the underlying gravel beds there was "no water" at first, but after going a few feet deeper there was an abundant flow, that did not rise much in the shaft. This case seems to support the following interpretation.

The gravels encountered do not form an isolated pocket or lens, else it would have carried water full from the first. It must be a fairly continuous porous zone with large feeding connections else it would run dry, and it must have an easy discharge else it would have risen above the level of the first gravels. Therefore it must be a rather well marked subterranean water passage or porous zone of considerable extent. Such conditions would make an impervious core wall to bed rock at this site a necessity and its construction a matter of considerable difficulty. At this site also because of the small cross section of the ridge, there is little chance for the interlocking of layers or the blocking of the porous ones by a till barrier to check the lateral seepage, and there is no chance to move farther down stream to secure such conditions.

4 Summary

Because of the (*a*) higher bed rock throughout, and (*b*) the more uniform and impervious quality of drift deposits, and (*c*) the more massive cross section of drift barrier for foundation, and (*d*) the perfectly tight contacts of till and bed rock, and (*e*) the limitation of the more porous materials to higher levels and (*f*) the glacial history connected with the development of all these parts, "*Olive Bridge*" is the preferable location for the proposed Ashokan dam on Esopus creek.

CHAPTER V

CHARACTER AND QUALITY OF THE BLUESTONE FOR STRUCTURAL PURPOSES

Probably no stone marketed in New York State is more extensively known than the "bluestone" of the Catskill region. But it is noted particularly for a special purpose, i. e. as flagstone, because of its capacity to part or cleave into thin slabs. These slabs are proven by experience to have remarkable weather resistance and durability.

Little attention has been given to the question of dimension stone — whether or not such blocks of as high quality as the flags could be obtained and where such quarries could be opened.

There are several reasons for this situation. In the first place (1) the stone is of a dark color and has a dull appearance so that it is not fancied for the usual expensive structures where large sizes are used, also (2) the quarries are small, shallow, and are worked on a small scale by single individuals or groups of neighbors with few quarrying tools and no transportation facilities for large material, and in addition (3) considering the work and equipment necessary and the demand the flag industry was more profitable.

Because of the large demands of the Ashokan dam where nearly a million cubic yards of heavy masonry construction are to be used an entirely new situation has developed. It is especially desirable that a rock capable of furnishing heavy dimension blocks should be discovered. The usual slab or flag type is unsuited to a considerable part of this work. A study of the adjacent region therefore has been made and explorations along certain promising lines have been conducted to sufficient completeness to prove that a suitable stone can be furnished in large quantity. The characteristics of structure and occurrence as shown by this special study are given, together with some of the later exploratory data.

Physiographic features[1]

All of the rock formations are sedimentary, chiefly sandstones and shales. They lie in alternating beds of variable thickness and are almost horizontal. The total thickness is many hundred feet so

[1] The principal argument of this discussion has been used in a previous article by the writer under the title "Quality of Bluestone in the vicinity of the Ashokan Dam" in the School of Mines Quarterly, v. 29, no. 2.

that neither the bottom nor the top beds of the series are to be seen in this locality.

The region is one of considerable relief representing preglacial erosion. The glacial drift mantle has modified it chiefly by obscuring some of the smaller irregularities of rock contour, and especially by partially filling many of the stream gorges. Postglacial erosion has not completely reexcavated the old channels. But the contour of the uplands reflects the character of the bed rock with considerable success. The tendency of the more massive and coarse grained varieties of rock to resist weathering and erosion more successfully than the finer grained and more argillaceous or shaly facies is a general characteristic. Since these varieties form successive or alternating beds throughout the whole area, the result is an almost universal cliff-and-slope surface form. This bed rock topography is somewhat obscured but not wholly obliterated by glacial erosion and deposition. Therefore it may be used with confidence in locating or tracing the more durable beds since they almost invariably appear as a shelf or terrace with a steep margin toward the lower side and a gentle slope on the rising side.

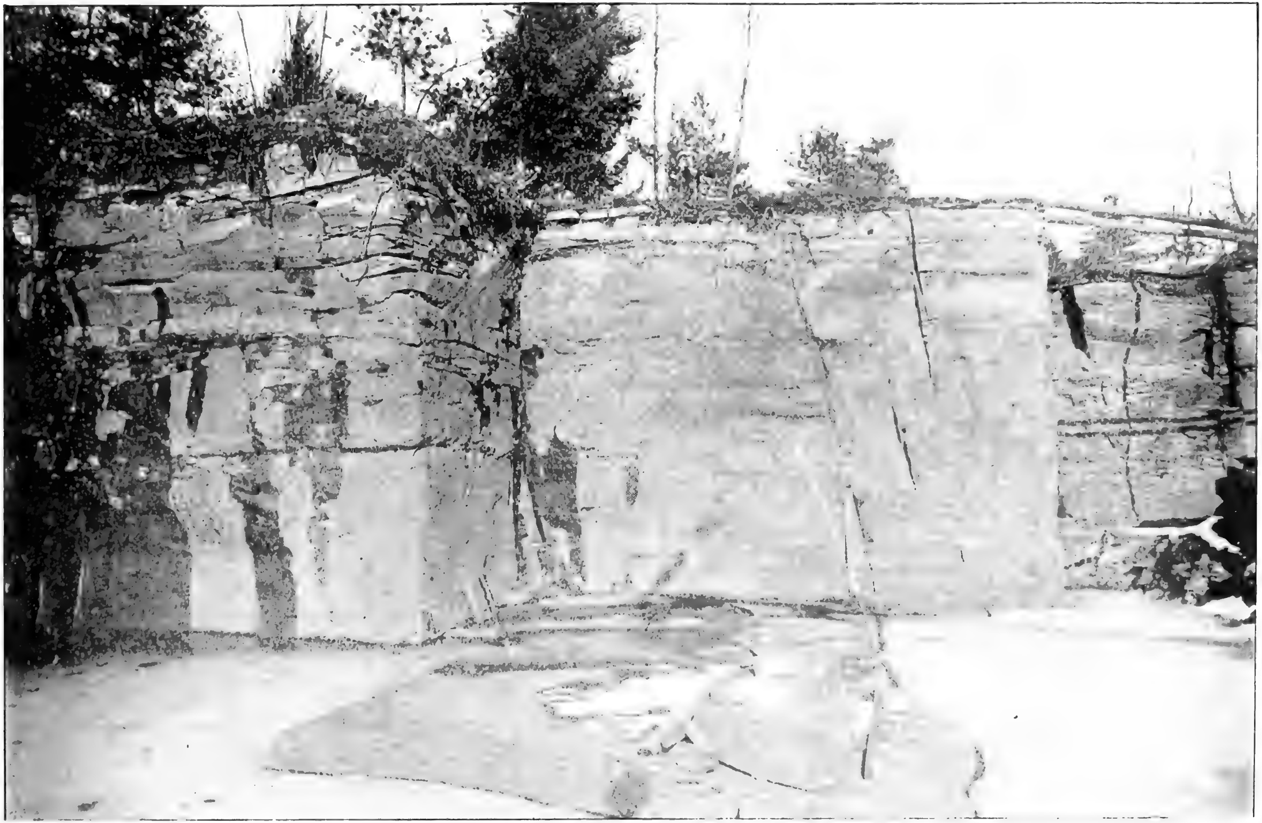
Structural features

The rock types include bluish gray or greenish gray sandstones with almost horizontal bedding, and sometimes exhibiting cross-bedding structure, and compact very dark argillaceous shales. These two are of about equal prominence, but only the sandstone is of importance in the present discussion. Its minute structure will be given in greater detail in the petrographic discussion.

Jointing is common and persists in two sets nearly at right angles to each other — one striking northeastward and the other toward the northwest. In some of the best exposures, these joints are clear-cut and run 10 to 18 feet apart, dipping almost vertically. In the more massive beds there is very little small jointing, so that the character is especially favorable to large dimension work.

But still more prominent structures are the partings which follow the bedding planes. These give the rock a decided tendency to cleave naturally into slabs, the uppermost exposed portion of almost every outcrop exhibiting this slab structure in more or less perfection. So general is this structure at all horizons in the sandstones of the series that there can be no doubt of its connection with some original sedimentation character. Besides it is a potential factor in nearly all the beds even when not very apparent. The

Plate 21



The Sherburne flags, showing their horizontal bedding and two very regular and prominent sets of joints. (Photograph by Board of Water Supply)

exposed places exhibit the character so prominently only because of the weathering effect, which develops the natural tendency. This general conclusion is borne out by the well known practice of quarrymen of the district of splitting the larger blocks into slabs of the required thickness by wedges driven along certain streaks that are known as "reeds." A reeding quarry is one that has this capacity well developed, and it is this character in part that has made the "bluestone" or "flagstone" of New York an important factor in the production of the United States for a great many years.

For large size dimension stone where great stress is involved it is evident that this structure would not be desirable. These definite planes of weakness reduce the general efficiency. A little observation however shows that there are some outcrops and an occasional quarry where the more massive blocks do not split well. From the necessities of the industry these have been avoided or but meagerly developed. In some cases of this kind the sedimentation is of the cross-bedded type with somewhat interlocked laminae. If the grain is coarse such varieties resist splitting with great success. The thickness of such beds varies from a few feet to 25 feet or even more without prominent interbedding of shale layers.

Stratigraphy. These are the sandstones, flags and shales known as the Hamilton, Sherburne and Oneonta formations belonging to the Devonic period. The strata of the immediate vicinity of this examination belong to the Sherburne subdivision, but no attempt to differentiate the formations was made. Structurally and petrographically the different formations are not distinguishable in this area. On the market the stone from either is known generally as "Hamilton flag" or "bluestone."

Economic features

There are hundreds of quarries in this general region. Nearly all are small, and are worked on a small scale without machinery. The product is almost wholly thin slabs of the flagstone type. This is supplemented by a small amount of somewhat more massive character, dressed for window sills; and a very limited output is of dimension stone of larger size. The general lack of suitable mechanical devices and transportation facilities are the chief reasons for the limited output of the last named grades.

Petrography

The basis of this discussion is a microscopic examination of several thin sections made of the different types of rock from the

quarries whose field geologic features give promise of encouraging results. The most characteristic variations are illustrated in the accompanying photomicrographs, plates 22, 23.

Texture. The rock is granular, the individual grains varying from minute particles in the finer shale layers to three or four tenths of a millimeter in diameter in the coarser sandstone [pl. 23, lower figure]. The grains are seldom rounded. Jagged or frayed or elongate forms are the rule [pl. 23, upper figure]. There is no marked porosity. When the rock was first deposited as a sediment it probably had the usual large interstitial spaces of such rock type, but in this case some subsequent modification — an incipient metamorphism — has largely obliterated the voids by the introduction or development of mineral matter of secondary origin.

In general it is quite apparent that the average grain was originally more rounded than its present representative.

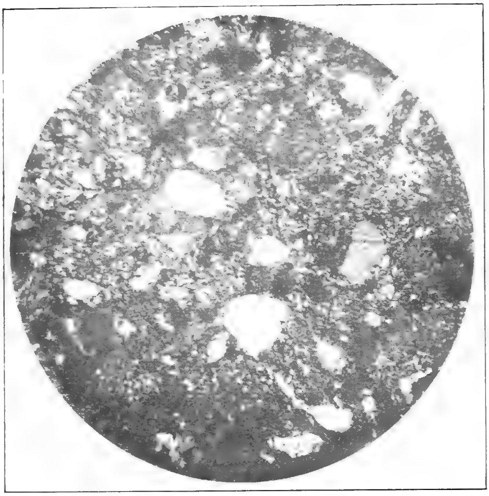
Mineralogy. The original minerals in order of abundance were the feldspars, quartz, and probably hornblende, biotite, and in much smaller amounts others of little apparent consequence in the present discussion.

All of these have been more or less affected by subsequent changes. Quartz has suffered least of all, the chief modification being a greater angularity of form and an occasional interlocking tendency caused by secondary growth [pl. 22, lower figure].

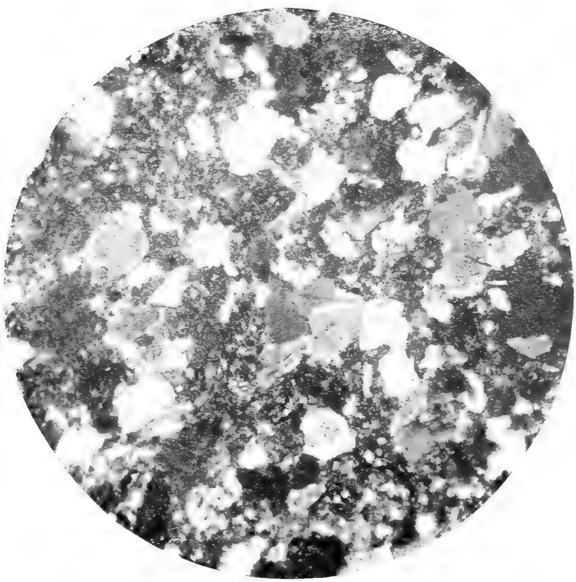
Both orthoclase and plagioclase feldspars occur. The orthoclase grains, which originally made up more than half of the bulk of the coarser types of rock, have been in places profoundly altered [pl. 22, upper figure]. In many cases the identification of this mineral depends upon its association and the abundant remnants of characteristic structure and its normal secondary products. In the least affected grains satisfactory identification is not difficult. Even in the most modified representatives there is some preservation of structure indicating size of grain and proving the essentially granular character of the rock. The plagioclase, although not abundant, is more readily detected than the orthoclase because it has been much less affected by the secondary changes.

All original ferromagnesian constituents are wholly altered. There were some such constituents in the rock, as is plainly shown by the secondary products. Hornblende and biotite were probably both present.

The secondary products, derived from the original feldspars and ferromagnesian constituents, include sericite, chlorite, calcite and



Photomicrograph of bluestone, x 25 diameters. The clearer grains are quartz and indicate the approximate size of other original constituents. In this case the alteration of the feldspars and ferromagnesian originals is so complete that their products form an indeterminable complex aggregate of closely interlocked granules, flakes, and fibers of extremely fine texture.



Photomicrograph of first grade medium grain bluestone, x 25 diameters. Taken to show angular and interlocking grains indicating secondary growth and a complete lack of reeding structure. The clear grains are quartz; the rest of the field is made up chiefly of secondary derivatives from the original feldspars and ferromagnesian minerals.

quartz as the most important and abundant. Others probably occur that are less readily differentiated, and among them is kaolin. Occasionally a small amount of massive or granular pyrite occurs. There are traces of organic remains, especially plant stems, and the pyrite is most plentiful in association with those beds.

It seems to be the secondary products largely that give the characteristic bluish or greenish color to this stone. Practically all of the iron freed by secondary changes from the ferromagnesian constituents has entered into new silicate compounds, especially with the chlorite, which are minutely distributed throughout the whole mass, giving it all a tinge of the characteristic color of these well known products. The same amount of iron in the oxid form would no doubt give as highly colored stone as any of the reds or browns of other familiar types of sandstone. But the tendency to form the sericite-chlorite-quartz aggregate in the rock has also an important bearing on its durability and strength. This is further discussed in a separate paragraph.

Classification. It is clear that this type of bluestone is a sedimentary rock of medium grain, a sand rock or "renyte." Since the silicates are so predominant in the original composition it may be further identified as a sandstone or a "silicarenyte." But in view of the predominance of the feldspars it should be further designated as an arkose sandstone. And considering the extent to which it has been modified by the development of interstitial silicious products and the effect that this has had in perfecting the bond between the grains, the rock may be classified as an indurated arkose sandstone.

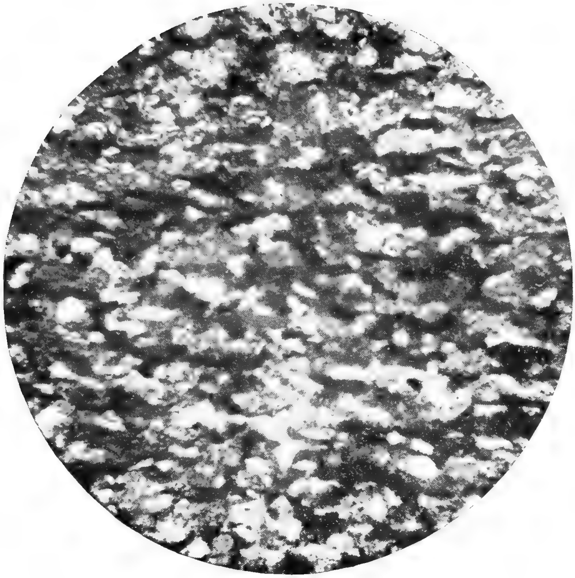
Special structure. A study of the cause of reeding, or the tendency to split into slabs, led to the preparation of thin sections of this structure [pl. 23, upper figure]. It is apparent from them that the reed is strictly a rock structure and that the perfection of the capacity to split along these planes depends wholly upon the abundance and arrangement and size of the elongate and semifibrous grains and the presence of a more than usual amount of original fine or flaky material. Almost universally the reed streaks are darker in color and finer in grain than the average of the rest of the rock.

In part therefore it is an original character due to the assorting action of water during deposition, finer streaks alternating with coarser ones in accord with ordinary sedimentation processes. But, in addition to that, the subsequent changes that have affected the whole rock have occasionally accentuated the structure by a ten-

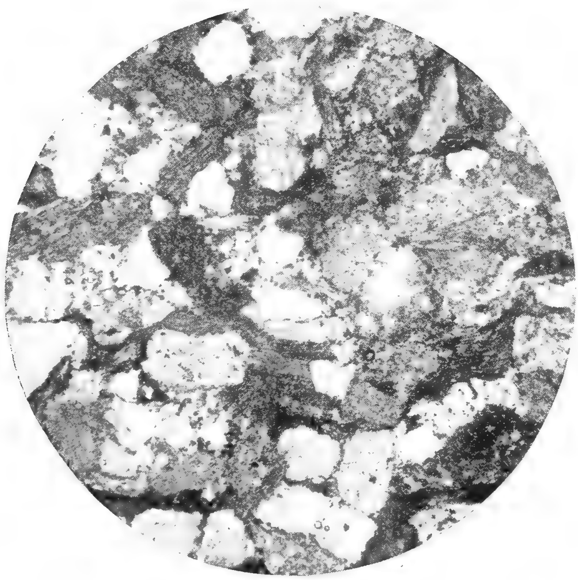
dency of the whole rock to develop elongate or fibrous aggregates. It is probable therefore that the parting capacity is in places considerably increased by the very process that has produced just the reverse results in the more heterogeneous portions of the beds.

Under a sufficient stress the rock will part most easily along the planes where this foliate or fibrous character is most persistent. Even in these cases, however, it may not indicate that the rock is essentially weak. It simply locates the most vulnerable point in the stone. In many quarries these streaks are so abundant that only thin slabs can be obtained — the disturbances of ordinary quarrying being sufficient to cause parting. The deeper portions of quarries are, however, much less subject to such behavior. In all cases the greater slab development of the exposed portion of the ledge is an ordinary weathering effect, by which the same results are obtained slowly and naturally and more perfectly than can be secured artificially on the fresh material of the same beds. The expansions and contractions of changes of temperature, together with the rupturing effects of freezing water caught in the pores, serve finally to weaken every part of the rock. In this process the prominent reed lines give way so much in advance of the rest of the rock that they develop into true rifts and separate slabs appear. It must be appreciated that these ledges have been exposed an immensely long time compared with the probable requirements of any engineering structure, and that this weathering tendency does not mean a speedy disintegration of the freshly quarried blocks. Still it is advisable to avoid as many sources of weakness as possible and one of the ways is to select ledges where the stone does not have a reeding tendency, or in which the reed lines are interlocked, or wavy, or interrupted. These requirements are most fully met in the coarser beds and especially those exhibiting some cross-bedding. Two local quarries meet these demands to a marked degree.

Strength. The better qualities of bluestone have great strength. Even the reed lines are in many instances stronger and more durable than the regular quality of some other sandstones that are usually considered suitable building material. The secret of this exceptional strength lies in the modifications of texture that have resulted from the alteration and reconstruction of the mineral constituents. The breaking up of the orthoclase feldspar, and the accompanying changes in the ferromagnesian minerals, have furnished considerable secondary quartz, which has in part attached to the original quartz grains making them more angular and de-



Photomicrograph showing structure of the reeding quality of "bluestone." Magnification 30 diameters. Taken to show tendency to parallelism of elongate grains.



Photomicrograph of best grade coarse-grained bluestone. Taken to show a quality in which the granular character is still well preserved. The clear grains are quartz, the others are chiefly feldspars somewhat modified. The close interlocking and the development of fibrous or frayed structure and the bending or wrapping of some constituents are secondary effects.

veloping an interlocking tendency [pl. 22, lower figure]. At the same time the fibrous sericitic and chloritic aggregates have developed to such extent as to fill most of the remaining pores, and in many cases the fibrous extensions have actually grown partly around the adjacent quartz grains [pl. 23, lower figure]. The effect has been to develop a silicious binding of unusual toughness. This combination of changes has made a rock that is now remarkably well bound or interlocked for a sedimentary type.

Durability. First-class stone of the grades indicated above would have as great durability as any stone in the market, except perhaps a true quartzite. With the exception of the almost neglectable quantities of pyrite, occasionally found, there is no constituent prominently susceptible to decay. The rock as a whole mineralogically is stable and its texture indicates unusual resistance to ordinary disintegrating agencies.

General conclusions

From the microscopic study it is clear that the variety of rock most fully meeting the demands of heavy exposed construction are the coarser beds and those freest from reed and shale.

From the field study it is apparent that ledges of suitable character occur occasionally and that at least three such are not far from the Olive Bridge site.

From additional explorations it is certain that ledges of high grade rock occur, and that the grade varies rapidly in the same bed and that suitable material can be obtained in the immediate vicinity of the Ashokan dam. No doubt rock of equally high quality may be obtained at many other localities.

CHAPTER VI

THE RONDOUT VALLEY SECTION

Because of the fact that the hydraulic grade of the Catskill aqueduct as it approaches the Rondout valley is nearly 500 feet A. T., an elevation more than 300 feet above the lowest portions of the valley and more than 200 feet above very large areas of it, a total width of more than 4 miles being too low for unsupported construction of some kind, and because of the general policy of using the pressure tunnel system so as to deliver the water at a corresponding elevation on the east side of the valley, and further because of the very complicated geological features of the district this section has been the seat of very extensive and interesting explorations.

Undoubtedly a greater number of obscure features occur here than on any other single section of the whole aqueduct line. Most of these features are readable from surface phenomena in general terms. In all cases the indications are plain enough to serve as a guide to well directed tests, but many points of critical importance can not be determined with sufficient detail and accuracy of position for such an engineering enterprise without systematic exploration.[1] The basis and results of this line of investigation which has occupied the greater part of two years are summarized and plotted in the following discussion and charts. The portion receiving special study is in the vicinity of High Falls.

General geology

Almost everywhere the surface is glacial drift. Where outcrops of bed rock occur they habitually present the unsymmetrical ridge appearance usually with a more or less sharply marked escarpment on one side and a gentle slope on the other. The strike of these

[1] These explorations belong to the Esopus division of the Northern Aqueduct Department. The earliest reconnaissance was done under the direction of James F. Sanborn, division engineer, who was subsequently assigned to geologic work over a con iderable portion of the Aqueduct line. The development of exhaustive explorations and final construction on this division has been carried on under Lazarus White, division engineer, assisted by Thomas H. Hogan. The division has been recognized from the beginning as an important one and in many ways one of the most complex. Thomas C. Brown, now professor of geology in Middlebury College, was employed for a year on this division during the later exploratory work.

features is in general northeasterly and on the gentle slope is the westerly one.

It is apparent at once that the valley bottom is a complex one and that its history has been somewhat obscured by the glacial deposits.

Formations. The following distinct stratigraphic units are determinable in this valley every one of which will be cut by the tunnel beginning at the west side with the youngest formations:

	Feet
Hamilton and Marcellus flags and shales	700-+
Onondaga limestone	200
Esopus gritty shales	800-+
Port Ewen shaley limestone including the Oriskany transition	250-+
Becraft crystalline limestone	75
New Scotland shaley limestone	100
Coeymans limestone	75
Manlius limestone including Rosendale, Cobleskill, and the cement beds	100-+
Binnewater sandstone	50
High Falls shale including small limestone layers	75
Shawangunk conglomerate 250 to	350
Hudson River slates — thickness unknown; probably more than	2000
Approximately	4775

These occur in belts in succession more or less regularly from west to east. Most of the formations are quite uniform in the Rondout valley. The Shawangunk conglomerate is probably more variable than any other as shown by borings. Because of this general persistence of formation it is possible to estimate approximately the depth at which any particular lower member lies if some starting point can be identified. [For detailed description of the formation, *see* pt 1]

Structure. The principal irregularities are structural, rather than stratigraphic. The region on the west side of the valley, the margin of the Catskills, is but slightly disturbed and lies very flat, but the region on the east side, the Shawangunk mountain range and the cement district, has an extremely complicated structure. The Rondout valley, lying between them, is a transitional zone and passes from gentle dip slopes and folds in the westerly side to more frequent folds and thrust faults on the easterly side. In at least two thirds of the valley it would appear from surface evidence alone that the formations would dip uniformly westward, the only suspicion of additional complication being given by an occa-

A minor fold in the Binnewater sandstone and High Falls shale at High Falls on Rondout creek. (Photograph by Columbia University Summer School in Geology. 1907)

sional minor fold seen in the river gorge or an escarpment where the sedimentary character alone would hardly account for it [*see* pl. 24, High Falls]. Explorations have shown that the evidence of the minor structures is reliable and that disturbances occur at some places even to the extreme western margin.

Physiography. In spite of the drift cover which obscures many original inequalities it is readily seen that the prevalence of the gentle westerly dip over most of the area, together with the succession of so many different beds of varying resistance to erosion, have allowed the development of a succession of long dip slopes and steep escarpments on a more pronounced scale than the present topography shows. It is clear that the Rondout is really a series of these unsymmetrical valleys. The principal large dip slopes are formed by the Shawangunk conglomerate and the Onondaga limestone. In each case an original stream had adjusted its course fully to the structure and was shifting slowly by the sapping process to the west against the opposing edges of the overlying strata which form the bordering escarpment. One of these unsymmetrical valleys lies along the easterly base of the Hamilton escarpment and is continuous with the lower course of Esopus creek farther to the north. In the area under special study it is not occupied by a stream now but is filled with glacial drift so completely that the original stream has been evicted. It is evident, however, from computations based upon the average dip of the slope carried to the base of the escarpment that the bed rock floor ought to be from 200 to 300 feet below the present surface in the deepest portion. Borings have proven this to be the case both along the present line near Kripplebush and also on the first trial line across the Esopus at Hurley.

The same thing is true near High Falls in the center of the valley where Shawangunk conglomerate forms the dip slope and the escarpment is formed by the Helderberg limestones. In this case the drift filling is very deep also, and Rondout creek flows upon it quite independent of rock structure except where it has cut across the margin as at High Falls.

In the eastern half of the valley the hard Shawangunk conglomerate forms the chief rock floor and largely controls the contour by its own foldings and other displacements. Thus the Coxing kill tributary valley lies in a syncline of the conglomerate with occasional remnants of overlying beds as outliers adding some variety to the form. The Shawangunk mountains, as a physiographic

feature, owe their present elevation chiefly to the resistance of this conglomerate which serves as a protective member among the formations.

On the west side, the foothills of the Catskills form a part of the cuesta developed by the erosion of Paleozoic sediments, the inface coinciding with the escarpment along the lower Esopus and Rondout valleys at this point.

It is certain therefore that the drainage of the Rondout valley before the Ice age differed materially from the present lines. A stream, probably the original Rondout, followed near the western margin of the valley and joined the Esopus as it emerged from the Hamilton escarpment to turn northeast. Another which had cut somewhat deeper occupied the central portion of the valley and probably joined the Esopus at some point farther north — its lower course is not explored.

Practical questions

The chief practical questions to be given as full answers as possible are:

1 At what depth must the aqueduct tunnel be placed in order to be everywhere in substantial bed rock with sufficient cover to be safe?

2 Where are the most critical places — those whose geologic characters are such as to demand exploration? And at the same time which sections may be safely left without testing?

3 What is the rock structure and condition? And are there reasons for believing that the tunnel plan is not feasible at this point. If so, where can a better one be found?

4 What is the character of underground circulation of water?

5 What formations will be cut at the different points and which should be favored or avoided wherever possible?

From the fact that the present Rondout flows across solid ledges at High Falls and at Rosendale from 100 to 200 feet above the known rock floor of the preglacial gorge where explored it is clear that the present course is entirely different from the original. The Coxing kill, the third and most easterly of these streams is not so much disturbed although it also is shifted.

It is worth noting that the streams of this valley together with the lower Esopus and the Wallkill river have become so completely adjusted to the rock structure that they all flow up the larger Hudson valley, of which all form a part, and join the master stream

at an obtuse instead of the usual acute angle. They are essentially retrograde streams.

Explorations. Systematic explorations and tests are represented chiefly by drill borings through drift into the rock floor. These were supplemented by two test tunnels for working character of material and a series of tests on the behavior of certain of the drill holes, together with other tests on material. The results are embodied in the accompanying cross sections and the additional discussion of special features.

Detail of local sections

Kripplebush section. This from the first was regarded as one of the critical sections because of the buried gorge along the base of the Hamilton escarpment and because of the doubt as to the behavior of the Onondaga limestone. On the accompanying section the borings are plotted and the structure as now interpreted is indicated. The dip slope formed by the Onondaga limestone is covered by 200 to 250 feet of drift, mostly modified drift. The strong valley character of the rock floor is almost wholly obscured by the glacial deposits and the present brook, an insignificant stream compared to the preglacial one, occupies a position above the escarpment instead of above the old channel.

After a couple of the central holes were finished, it became apparent that the structure is not nearly so simple at this point as the general surface features would lead one to expect. It was clear that a simple dip such as was proven to prevail on the dip slope would not account for the much greater depth attained by it in the vicinity of station 500. The discovery of this additional feature raised two questions: (1) Is the structure a flexure or is it a fault, and if a fault whether normal or thrust, and (2) what is the probable effect of this structure on the position and depth of the preglacial gorge?

The habit of the district immediately east of the valley would support the theory of a thrust fault. The nature of the immediate area would suggest a simple flexure while it is manifestly possible that a normal fault could easily occur. Later explorations[1] have

[1] Since the above was written the tunnel has been completed through the Kripplebush section. Although faulting is indicated by the borings and actual occurrence of the beds it is very difficult to find the fault. A part of the displacement is accomplished by the steepening of the dip but this will not account for more than half of it.

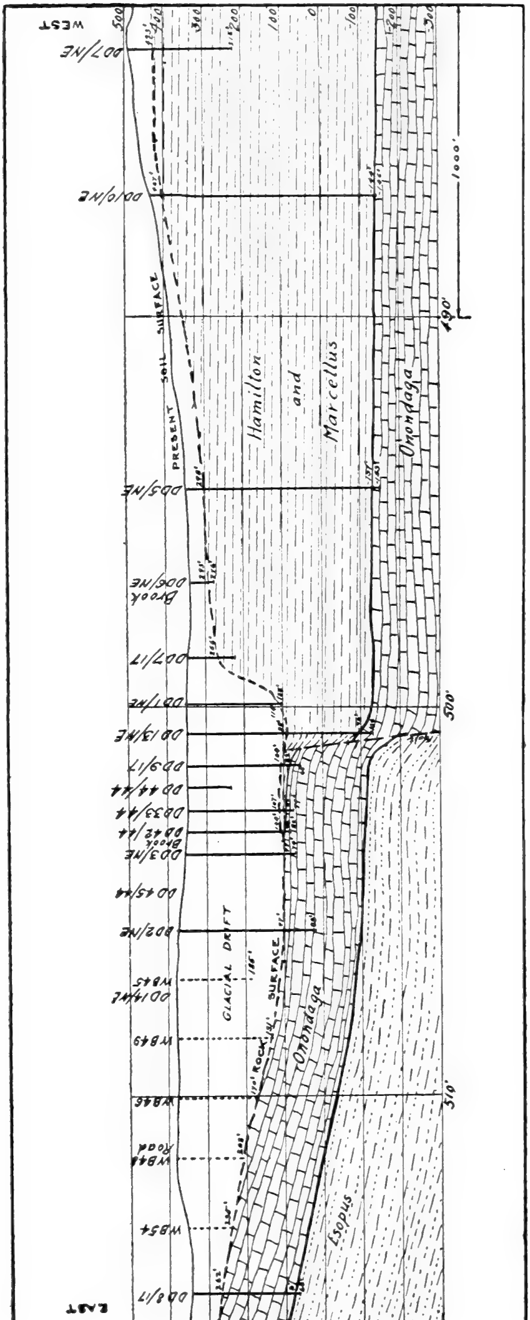


Fig. 19 Geologic cross section of the Kripplebush section of the Rondout tunnel line as interpreted from drill borings

tested this zone so well that it is practically certain that the feature must be regarded as a fault of some type with a displacement of nearly 200 feet. The striking physiographic feature is the development and preservation of the escarpment on the downthrow side. This occurrence is certainly a very unusual case in that regard [*see* fig. 19].

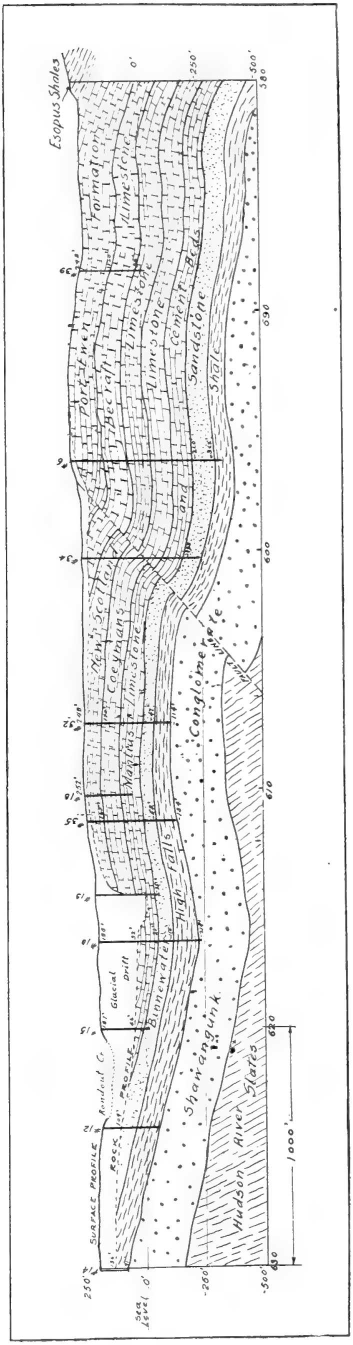
Because of the intention to construct the tunnel deep enough in bed rock to reach safe rock conditions the question of depth of buried gorge becomes an important one. As soon as it was discovered that a fault existed there the problem became of sufficient prominence to demand more detailed exploration. If the faulting is accompanied by a broken zone in condition favorable to more ready erosion, it would be possible that the original stream in working down this dip slope might become entrenched in the fault zone and at that point begin to cut a narrow gorge instead of continuing the sapping process. In fact, it would undoubtedly do this very thing if there is such a crushed zone of any consequence and if the erosion process were allowed to continue long after reaching this critical point.

As a matter of fact explorations have shown that there is a thin layer of Hamilton shales still remaining on the Onondaga and the deepest point found is on the Hamilton shales side. These facts in connection with the failure to find any deep notch indicate that there is probably no zone of much greater weakness than the shale member itself. It is reasonable to conclude that the rock floor can be safely regarded as not much lower than 88 feet A. T. and that the rock condition is not especially bad for tunnel construction[1] even in the fault zone.

Rondout creek section. This is the central portion of the valley including the depression occupied by the present Rondout and the exposed edges of the series of shales and Helderberg limestone. The repetition of the dip slope and escarpment, together with the heavy drift filling and the occurrence of so many formations together make this an important section. All formations from the Shawangunk conglomerate to the Port Ewen shaly limestone occur at this point, and although there is little outward evidence of disturbance it is certain that whatever difficulty is to be found in this variable series is likely to be met here. It is therefore a section that requires exploration both for depth of preglacial channel and for quality of rock.

[1] In construction this ground has proven to be good and sound throughout.

WEST



EAST

Fig. 20 Geologic detail of the central Rondout section constructed from exploratory borings data

All of the formations dip westward wherever exposed, but the dips vary somewhat, nearly all being of low angle. Occasional minor inequalities of the nature of small rolls may be seen, as, for example, the small fold in the gorge at High Falls [*see* pl. 24].

Explorations have shown, as indicated on the accompanying cross section [fig. 20], that there is a deeper buried gorge here than at Kripplebush. The deepest point discovered is a few feet below tide level. The escarpment is steep and is formed by the Coeymans and New Scotland formations. The dip slope is Shawangunk conglomerate, High Falls shale and Binnewater sandstone, with the Manlius limestone forming the floor.

Identification of the drill cores which penetrate the limestone indicate that the dip slope is reversed on the west side of the gorge and that the stream had really reached about the axis of the trough. A discrepancy in thicknesses and depths in hole no. 34 by which it appeared that the Coeymans formation was almost twice as thick as usual and that it contained a broken or crushed zone leads to the interpretation that there is a small thrust fault here which repeats the formation as shown on the accompanying cross section.

Instead of a uniform westerly dip of all formations from the Rondout westward it is proven that minor anticlinal rolls and even thrust faults, as in this case, or such faults as in the Kripplebush case are not to be excluded.

This structural relation has a direct bearing upon the question of the thickness of the Esopus shales. The Esopus is certainly not so thick as would otherwise be supposed, by 200 or 300 feet at the least. The true thickness is still an unknown quantity (estimated at 800 feet).

It is clear that the aqueduct tunnel will have to be constructed a considerable depth below sea level at this section, probably not less than minus 150 feet,[1] even if the character of the formations be neglected.

But the character or quality of these formations in view of their structural relation constitutes the chief problem. Because of the fact that every structure reaches the surface and eventually dips gently to the west in such manner as to encourage water circulation, their water-carrying capacity or general porosity becomes of great importance. A great capacity is all the more serious because of the heavy drift cover within the abandoned gorge, on top of which

[1] This portion of the tunnel and its continuation south to the Shawangunk range has been constructed at 250 feet below sea level.

the stream flows and which constitutes essentially an unlimited storage reservoir to feed underground circulation. This is all the more true if crush zones are extensively developed as accompaniments of the faulting.

In general as to perviousness the indications are somewhat obscure. But the data now obtained seem to prove that all the formations except the Binnewater sandstone and the High Falls shale are compact and fairly impervious along the bedding lines. Only where crevices have formed or where crushing occurs is there likely to be heavy circulation. This is all the more important since so many of the beds are limestones known to be readily soluble in circulating water. One of these limestones, the Manlius, exhibits occasional large open solution joints at the surface — so large that a surface stream disappears entirely at the so called "Pompey's cave" and joins the subterranean circulation. But such caves are probably limited to the surface.

It is near this point, however, that one of the earlier borings at one side of the present line discovered very soft ground at a depth of about sea level, i. e. over 200 feet below the present surface, which shows that similar conditions prevail at certain points to great depth.

Pumping tests made on hole no. 32 in an attempt to establish some data on the inflow of water gave very interesting results. These tests were very thorough. It was proven that the water was supplied in apparently inexhaustible quantity at maximum pumping capacity, which was ninety gallons per minute. Futhermore, the chief inflow seemed to be from the Binnewater and High Falls formations as was to be expected. Whether a crush zone allowing free circulation is furnishing a portion of this supply or whether the whole inflow represents the normal porosity condition of these formations is not yet proven.[1]

Other porosity tests have been made in such way as to locate and measure this factor [*see* later discussion]. Hole no. 10 shows an artesian overflow that comes from the Binnewater sandstone. A working shaft has been put down also in the vicinity of hole no. 32 and at the same depth found an enormous inflow of water which drowned out operations for a time. The lateral supply in this case has been reduced by introducing a thin cement grouting through holes bored in the surrounding rock from the surface.

Holes no. 12 and no. 14 also show an artesian flow, but both are

[1] In construction the Binnewater sandstone has been found very wet.

shallow holes and the supply comes from near the contact between High Falls shale and Shawangunk conglomerate.

It is certain from these observations and tests therefore that the Binnewater sandstone and High Falls shale are more porous than the other formations, and because of the serious difficulties arising from so heavy inflow of water from them the tunnel grade should be shifted so as to avoid these formations as much as possible. A comparison of the accompanying cross section, which is drawn to scale [fig. 20], will show that a tunnel on one level would necessarily run for a long distance in these beds because of the gentle syncline. Furthermore, they lie at about the depth that would otherwise be a safe depth below the buried gorge. But a tunnel with a step-down, i. e. one run at two different levels could avoid most of this poor ground. By approaching at a level of about — 50 feet or — 100 feet in the limestone beds to station 600 (hole no. 34), then stepping down to — 250 feet, the line in a very short distance crosses these two porous formations and enters the Shawangunk conglomerate which is more substantial, and, all things considered, one that seems most advantageous for successful construction. It will have to maintain a head of more than 700 feet as the difference between hydraulic grade and the tunnel level in this section. Under these conditions rock quality and condition are of greatest importance and there is no doubt about the advisability of avoiding the poorest formations in some such manner.

Coxing kill section. On the line of exploration the Coxing kill flows over Shawangunk conglomerate and High Falls shale. Both dip plainly eastward, and a hole no. 11 located on the east side of the brook penetrates about 70 feet of drift and shale. But only a hundred feet to the east Shawangunk conglomerate outcrops at the surface dipping the same way. It is certain therefore that a fault occurs here. The dip of the fault plane is indeterminate from the surface, but the relations and surroundings indicate a fault of the thrust type.

Later explorations indicate that the fault plane is rather flat [*see* cross section fig. 21] so that the shales are repeated above and below a tongue of conglomerate. Boring no. 11 has also an artesian flow of considerable volume coming from near the bottom of the conglomerate. It is a mineral water.

The chief importance of this section as a problem in applied geology lies in the influence of the fault and the maximum depression of the conglomerate. If the tunnel, which enters Hudson River slates at the Rondout creek section at — 250 feet can be kept within that formation throughout the rest of its course,

there is no doubt that an advantage will be gained both in the greater imperviousness of the rock and the greater case of penetration. Wherever the conglomerate is undisturbed it is perfectly good, but where broken the crevices are but imperfectly healed and circulation is unhindered. It would therefore be desirable to know whether at — 250 feet the whole of the downward wedge of Shawangunk could be avoided. The borings indicate a thickness of Shawangunk of 345 feet in hole no. 11 where it is cut at a small angle, and a thickness of 409 feet in hole no. 36 where it probably lies pretty flat. This greater thickness together with the

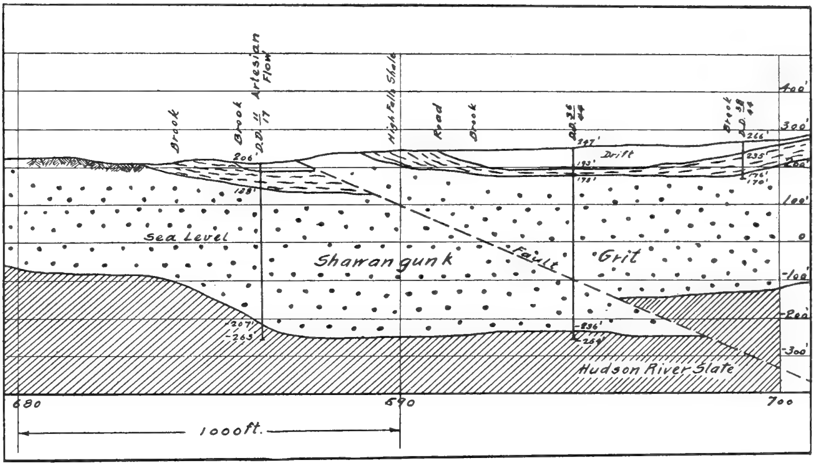


Fig. 21 Structural geologic detail of the Coxing kill section

finding of crushed rock at about the — 100 foot level leads to the conclusion that the formation is overthickened here by the thrust fault to the extent probably of about 75 feet. The true thickness of the formation at this point is doubtless more nearly 300 feet than either of the figures obtained directly from the two holes. If this interpretation is used as the basis of plotting a cross section [*see* accompanying cross section] it is apparent that the conglomerate should not be expected to extend more than a few hundred feet east of hole no. 36 and it probably does not reach a much greater depth than the — 236 feet represented as its base in that boring.[1]

[1] Construction of the tunnel has progressed far enough through this section to prove that the Shawangunk formation does not reach much lower. It forms the roof of the tunnel for some considerable distance but does not come down into the tunnel more than a foot or two.

Shawangunk overthrust. At the extreme eastern side of the Rondout valley near the point where the surface reaches hydraulic grade again, the surface outcrops pass from High Falls shale to Shawangunk conglomerate to Hudson River shale in the normal order but with entirely too small an area of conglomerate considering the character of the formations. The higher ground is all Hudson River in the vicinity, and there is abundant evidence of crushing and disturbance. It is evident that a thrust fault is again encountered here, one of sufficient throw to bring the Hudson River slates above the Shawangunk conglomerate — probably a lateral displacement of very great extent. Explorations have fully proven the existence of this fault. The accompanying diagram shows a cross section as now outlined by complete penetration of two borings.

Two trial tunnels were run to test working quality of Hudson River slates compared to Shawangunk conglomerate at this locality. Both are within the influence of the fault zone. Both are therefore more broken than the normal with the result that the Hudson River slates probably show poorer condition than usual and more troublesome working, while Shawangunk conglomerate probably shows easier working than usual. It is believed that normally the two rocks would present a greater difference than was found in this test.

Special features

Several questions, some of which have a practical bearing, have been raised as separate features during the exploration of the Rondout valley.

Caves. One of these is in regard to the possible existence of underground caverns. This was given a special prominence early in the work by the experience of one of the drills. After penetrating the limestone series near High Falls to a depth of over 200 feet, the drill seemed to leave the rock and enter a space allowing the rods to drop 28 feet before being arrested by solid material. The further attempt to work in this hole resulted in the breaking of the rod down at this point and the subsequent failure to recover the diamond bit which is still in the bottom of the hole. The question is as to the meaning of this occurrence. Is it a cavern?

"Pompey's cave" has been referred to in an earlier paragraph. This is clearly not much of a cave. It is essentially an enlarged joint or series of joints by solution along the bed of a surface

stream to such extent that the stream normally at present has become subterranean. It is the writer's opinion that the case encountered by the drill boring is similar. The apparent cavern is probably a slightly enlarged joint along a line of somewhat abundant underground circulation and perhaps associated with some crush zone developed by the small faulting known to occur in this immediate vicinity. It is probably not entirely empty but contains residuary clay, and in all likelihood is very narrow and not exactly vertical, so that the drill rods were bent out of their normal course and wedged into the lower part of the crevice. Smaller spaces of this sort were encountered at a few other points.[1]

These occurrences seem to indicate that the limestone beds yield rather readily to solution by underground water, and that this circulation has been at one time active to at least 50 feet below present sea level. With present ground water level nearly 200 feet above sea level it is extremely unlikely that any such action is going on at so great depth. The occurrence is therefore strongly corroborative of former greater continental elevation when the deep stream gorges, now buried, were being made. These deeper caverns or solution joints probably date from that epoch.

Imperviousness and insolubility. The question of imperviousness and closely associated with it that of solubility, is of great practical importance in this particular work. The immense pressure under which the tunnel will be placed in crossing this valley makes it impossible to construct a water-tight lining. Everywhere much depends upon the rock walls to help hold the water from serious loss. Wherever the rock is fairly impervious except occasional crevices or joints they can be grouted and safeguarded satisfactorily. But where a formation is of general porosity this can not be so successfully done. Even more difficult to handle is the rock wall which is soluble and which therefore with enforced seepage may tend to become progressively more porous. That this consideration is not wholly theoretical is shown very forcibly by the Thirlmere aqueduct of the Manchester (England) Waterworks. In that case a 3 mile section was built through limestone country using the same local limestone for concrete aggregate. Although

[1] In constructing the tunnel several clay-filled spaces have been discovered in the same vicinity at elevation—100. One of these extended vertically with a width of 1 to 2 feet and from it a great mass of mud ran into the tunnel. At one point it was connected with a horizontal space of the same kind extending 15 feet. It can be seen that the original crevices have been enlarged by water and that they were originally formed during faulting.

this concrete was mixed as rich as 1 part cement to 5 parts aggregate and the work was well done, excessive leakage reaching a total of 1,250,000 imperial gallons per day was developed within a year. It was found that the limestone fragments of the aggregate were corroded forming holes through the lining of the aqueduct and that these holes actually enlarged outward. All this was done under cut and cover conditions with not more than a 6 or 7 foot head on the bottom of the aqueduct.

In the Rondout valley, the aqueduct will cut no less than 6 limestone beds in all cases under great pressure. This fact will in all probability tend to increase the action. But, of course, some of the beds may not yield so readily to solution. Tests made thus far, however, indicate that all are attacked in water. Considering these facts it seems desirable, so far as possible, to avoid the limestone beds wherever rock of greater resistance to solution can be reached, and further it is equally desirable to use a more resistant rock for the lining concrete. So long, however, as the formation is not very pervious so that a new circulation could not be established by the escaping water there would be little harmful effect.

An average of five analyses of the Thirlmere limestone, different varieties of the same formation, gives the following:

Insoluble silicious matter	2.772%
Alumina and iron oxid $Al_2O_3+Fe_2O_3$	0.276
Lime, CaO	53.676
Magnesia, MgO	.390
Carbonic anhydrid, CO_2	42.248
Total	99.362

Estimated calcium carbonate, $CaCO_3$ — 95.85%

The limestone is fossiliferous.

Suitable analysis of the limestones of the Rondout valley are not recorded in sufficient numbers. But these are a few, as given below.

BECRAFT LIMESTONE.	At Rondout	At Wilbur	At Hudson (av'ge of 2)
SiO_2	3.87%	7.10%	1.865%
Al_2O_3	1.07	2.50	.818
Fe_2O_3	1.34	1.65	1.185
CaO	54.11	45.32	51.375
MgO	tr	tr	2.870
CO_2	40.60	39.10	40.795
Total	100.99	95.67	98.908
Corresponding to total calcium carbonate	96.62	80.75	91.74

This is a limestone that in composition and structure at the Rondout valley is apparently not very different in quality from the Thirlmere rock. Analyses of the cement rock show less similarity but observations indicate that it is also attacked.

It is probable from all these facts that the shales and conglomerates are better quality of wall than the limestones.

A very acute observation along this line by Dr Thomas C. Brown while employed on the staff of the Board of Water Supply is of special interest. In studying local conditions he noticed that the limestone blocks used in building the old Delaware and Hudson (D. & H.) canal showed the effect of contact with the water. The best place for measurable data seemed to be around the old locks where squared and evenly trimmed blocks had been used. These were, during the years of its use, from 1825 (approximately 35 to 40 years) subject to the action of water flowing or standing in direct contact. The coigns of the locks, which were without doubt freshly and well cut when laid, are now etched till the fossils and other cherty constituents stand out from one eighth to one half inch beyond the general block surface, and in some cases the pits are an inch deep. That this etching is due to the water rather than to exposure to weather is shown by the lack of such extensive action on blocks used in houses and exposed a much longer time. Blocks representing the Manlius and Coeymans were identified. But there is no reasonable doubt that others would be similarly affected. On some it would be less easily detected.

On account of the disturbances another factor is introduced. Rocks which readily heal their fractures are likely to furnish better ground, i. e. more free from water circulation especially, than rocks more brittle and slow to heal. Therefore in this district the shales and slates such as the Hudson River series and the Esopus and Hamilton shales are the best ground, while the Binnewater sandstone is the poorest.

Cross sections. Probably in no region of like extent is it possible to construct a geologic cross section of so many complex features so accurately as can now be done of the Rondout valley along the aqueduct line. The section is known or can be computed to a total depth below the surface of 1000 feet, including 12 distinct formations, so closely that any bed or contact can be located within a few feet at any point throughout a total distance of over 4 miles.

The accompanying cross section contains as much of this data as is now available [fig. 22].

Fig. 22 Geologic cross section of the Rondout valley
Constructed from the data secured in exploratory borings on the Rondout pressure tunnel line

Rondout siphon statistics

1 Total borings on the siphon line. Three different boring equipments have been used owned by different parties and records have been kept so that the work of each can be followed or compared with the others.

On this division the Board of Water Supply owned and operated one machine with their own men, another equipment was owned and operated by C. H. McCarthy, while a third which finally did a majority of the work, belonged to Sprague & Henwood, Contractors, of Scranton, Pa.

The totals of different general types of material penetrated by these machines are as follows:

	Feet of drift	Feet of rock	Total feet of depth	Per cent of core saved
a B. W. S. Equipment	1740.5	2175.5	3916	89.4
b Sprague & Henwood	3647	6831	10478	60.04
c McCarthy machine	181	1228	1409	78.1

The average saving of core by all machines, cutting all kinds of bed rock was 75.96%

2 Core recovery from various strata. So nearly as can be done the strata represented in the drill cores have been identified and summarized as to total penetration and core saving. The core saving is a factor of prime importance in judging of the quality of rock and its freedom from disturbance. The following items are gathered from a study of the whole series.

a Holes 6, 10, 12, 13, 15, 17, 18, 21, 22 and 25 penetrate Helderberg limestone, a total combined depth of 1096 feet. Individual holes vary in core saving from 39.3% (no. 13) to 95.3% (no. 15). The average core saving is 78.19%.

b Holes 8 and 9 are in Onondaga limestone with a total penetration of 197 feet. The core saving varies from 56.2% to 92.8% with an average of 74.5%.

c Holes 11, 19, 20, 23, 24, 27 penetrate Hudson River shale and together represent a total of 696.5 feet. The core saving varies from 16.6% to 89%, with an average of 42.1%.

d Holes 6, 10, 11, 12, 14, 16 and 20 cut High Falls shales to a combined total of 410 feet. The saving varies in different holes from 17% to 83.3%, with an average core saving of 44.5%.

e Holes 8 and 26 penetrate Esopus shale and penetrate 76 feet.

The core saving varies from 73% to 84.6%, making an average of 78.8%.

f Holes 10, 11, 12, 14, 16, 19, 20, 23, 24 and 27 penetrate Shawangunk conglomerate a total of 1356.5 feet. Core saving varies in different holes from 33.3% to 100%. The average recovery is 60.52%.

g Holes 6, 10, 12, 15 and 16 cut Binnewater sandstone. The total penetration is 205 feet. The range of core saving is from 30.6% to 74.7%, with an average of 56%.

h Holes 7 and 9 cut Hamilton shales to a total amount of 65 feet. The range of saving is 70% to 81.8%, with an average of 75.9%.

3 **Artesian flows.** Several of the borings struck artesian flow of water. The fact that the sources of this flow are not the same has led to a tabulation of these data.

RECORD OF ARTESIAN FLOWS

Hole no.	Size in inches	Static head in feet	Flow gallons Minute	Day	Flow encountered at elevation Feet	Strata
10	1	18	30	43 200	—109	....Binnewater sandstone
11	1	10	10	14 400	— 60	....Shawangunk conglomerate
12	⅜	1	....	......	— 24	....High Falls shales
14	1¾	......	....	......	+ 90	.... "
20	⅜	7.5	10	14 400	+108	....Shawangunk conglomerate
23	2	......	....	......	— 5	.... "
31	2	......	....	......	+158	.... "
39	1½	......	....	......	+112	....Helderberg limestone
5NE	⅜	12.4	....	432	+203	....Hamilton shale (possibly drift)

Pumping experiments and porosity tests

Systematic tests have been made for flow of water, behavior of ground water and porosity of rock on certain of the Rondout exploratory holes under the direction of Mr L. White, division engineer. A summary of these tests has been furnished by him from which is quoted the following:

In addition to determining the location and thickness of the beds and the general character and condition of the rock from inspection of the cores, serious attempts were made to determine the relative porosity and water-bearing quality of the rocks encountered for the following reasons. (1) To determine the probable leakage from the siphon when in operation. (2) To determine the probable amount of water to be handled in construction. These experiments were divided into three classes: (1) Observation of flow from cer-

tain drill holes which showed sustained flow of water. (2) Pressure tests in which water was pumped into holes which had been sealed off and pressure and leakage noted. (3) Pumping tests in which water was pumped from 4 inch drill holes by means of deep well pump of the type used in oil wells, and fall of ground water during pumping and subsequent rise after cessation of pumping noted. A description of the first two and the results obtained from them follows:

A substantial flow of water was observed from the following holes:

11/17: 50 gallons per minute through 2½ inch pipe, static head 10 feet

10/17: 30 gallons per minute through 1½ inch pipe, static head 18 feet

20/17: 10 gallons per minute through ⅜ inch pipe, static head 7.5 feet

The static head was observed by adding on lengths of pipe until the water ceased to flow over. It will be noticed in the case of hole no. 10 that the flow from the 1½ inch pipe is not that due to static head of 18 feet, but that due to a head of only ½ foot. In other words the friction head is about 17.5 feet, and the velocity head only ½ foot. This same condition holds true of the other holes from which a flow was obtained. This would seem to indicate that the amount of water is not very great but that it is under considerable pressure. It is believed that this pressure is caused by gas.

A slight flow was observed from the following holes: 12/17, 14/17, 23/17, 31/44, 39/22, and 5/NE.

The flow from most of these holes has ceased since the pipe used in boring was withdrawn. There is still some flow from the following holes: 11/17, 20/17, 25/17 and 5/NE.

The flow from hole 11/17 is constant at about 10 gallons per minute. The others are too small to be measured. It will be noted that the only substantial flows encountered were from the High Falls shale, Binnewater sandstone and Shawangunk grit, and that it was possible to force water into these rocks in greater quantities and at a less pressure than in the other shales and limestones.

Porosity tests. The method of making these tests was as follows:

Wash pipe equipped with a device for sealing the hole was lowered to the desired elevation. The seal consisted of alternate layers of rubber and wood around the pipe preventing the water from escaping between the walls of the hole and the pipe. Water was then pumped in and pressure and leakage noted.

The result of the pressure tests was to show in a general way: (1) That the pressure increased with the depth of seal. (2) That the leakage decreased with the depth of seal. (3) The maximum pressure in the grit was 140 pounds to the square inch and minimum

leakage was 5 gallons per minute. (4) In the Hamilton shales a pressure of 300 pounds to the square inch with very little leakage was obtained.

The unknown factors are too many and too great to make any reliable deductions from these experiments.

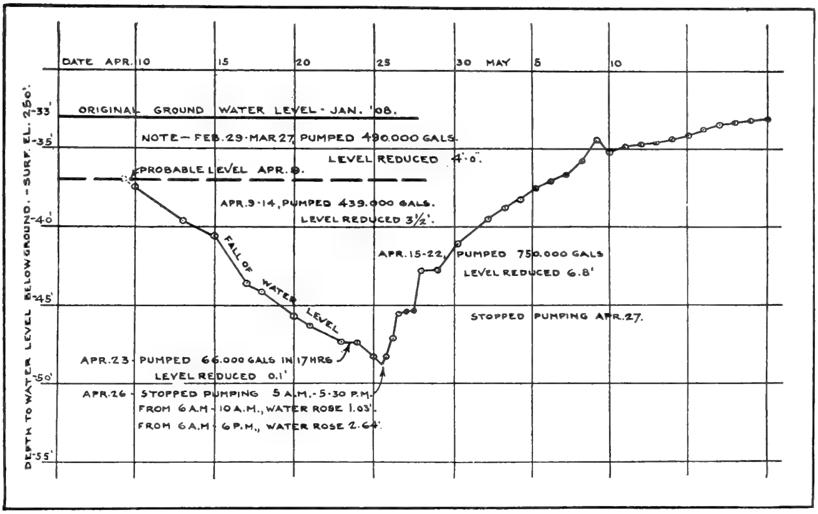


Fig. 23 Curve showing fall of ground water level while pumping from boring 34

Pumping experiments were carried on in holes 32/22 as follows: The apparatus used was a deep well pump of the type used in oil wells. The holes were of an inside diameter of 4¼ inches and were cased to the bottom. A 3½ inch working barrel was then lowered to the bottom of a line of wooden sucker rods. The stroke was 44 inches and the nominal capacity of pump at 38 strokes per minute was 60 gallons per minute or 86,400 gallons per day. The power was obtained from a 40 horsepower boiler and 35 horsepower engine belted to a 10 foot band wheel which was connected to a 26 foot walking beam. In hole 32/22 at station 607 + 50 the average discharge at 38 strokes per minute was 90 gallons per minute or 129,600 per day. The experiment was continued for 15 days and the total amount of water pumped was 1,071,000 gallons. The ground water level was not lowered. It will be noticed that the discharge at this point was 50% in excess of the theoretical capacity of the pump. This was caused by the presence of gas, the effect of which seemed to be increased by the churning action of the pump. This may also explain the failure to lower the ground water.

The experiment at hole 34/22 was similar in character. The upper 230 feet of this hole had an interior diameter of 4¼ inches

and the bottom 274 feet a diameter of only 3¼ inches. At first a 2¼ inch working barrel was used to pump from the bottom and a discharge at 32 strokes per minute averaged 24 gallons per minute or 34,500 gallons per day. This was continued for about 15 days and the total quantity pumped was 490,000 gallons. The ground water level was lowered 17 feet at hole 34 and 4 feet at hole 32, 750 feet away.

The 3¼ inch pump was then let down to a depth of 200 feet with a 2½ inch casing reaching down to the Binnewater sandstone, depth of 437 feet. The average discharge at about 40 strokes per minute was 60–65 gallons per minute, or an average of 90,000 gallons per day. It will be noted that the discharge was much smaller than at hole 32 owing to the absence of gas. Pumping with a 3¼ inch pump was continued 16 days and 1,532,000 gallons of

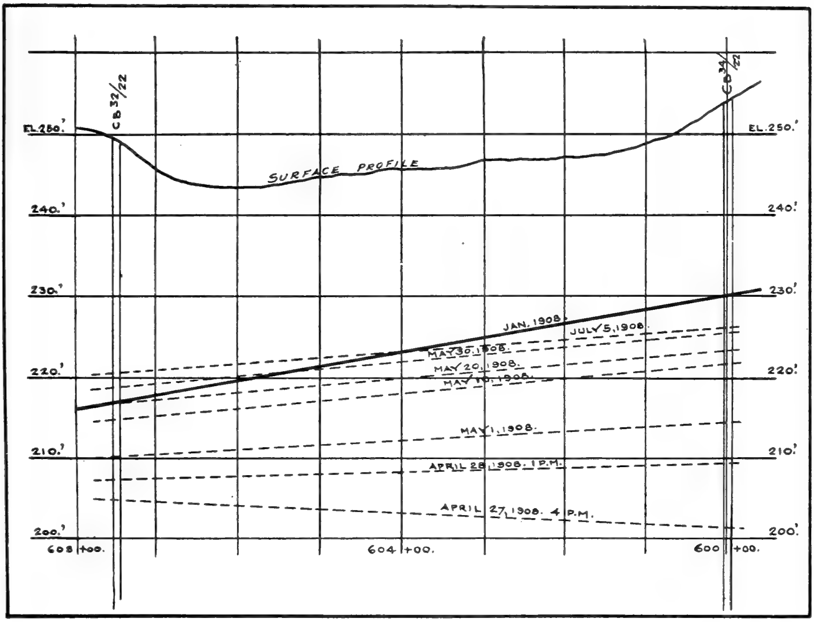


Fig. 24 Diagram showing successive stages of ground water level between holes 32 and 34 during pumping

water were pumped in addition to the 490,000 gallons from the 2¼ inch pump. The ground water level in hole 34 was lowered 36 feet in addition to the 17 feet by the 2¼ inch pump, but rose 9 feet in 20 minutes, and 30.5 feet in the next five days. In the next 22 days it rose 9.15 feet, or .42 feet per day.

Reduced water level in hole 32, 750 feet away by pumping in 34, 15 feet, or 1 foot for each 120,000 gallons pumped. In the first

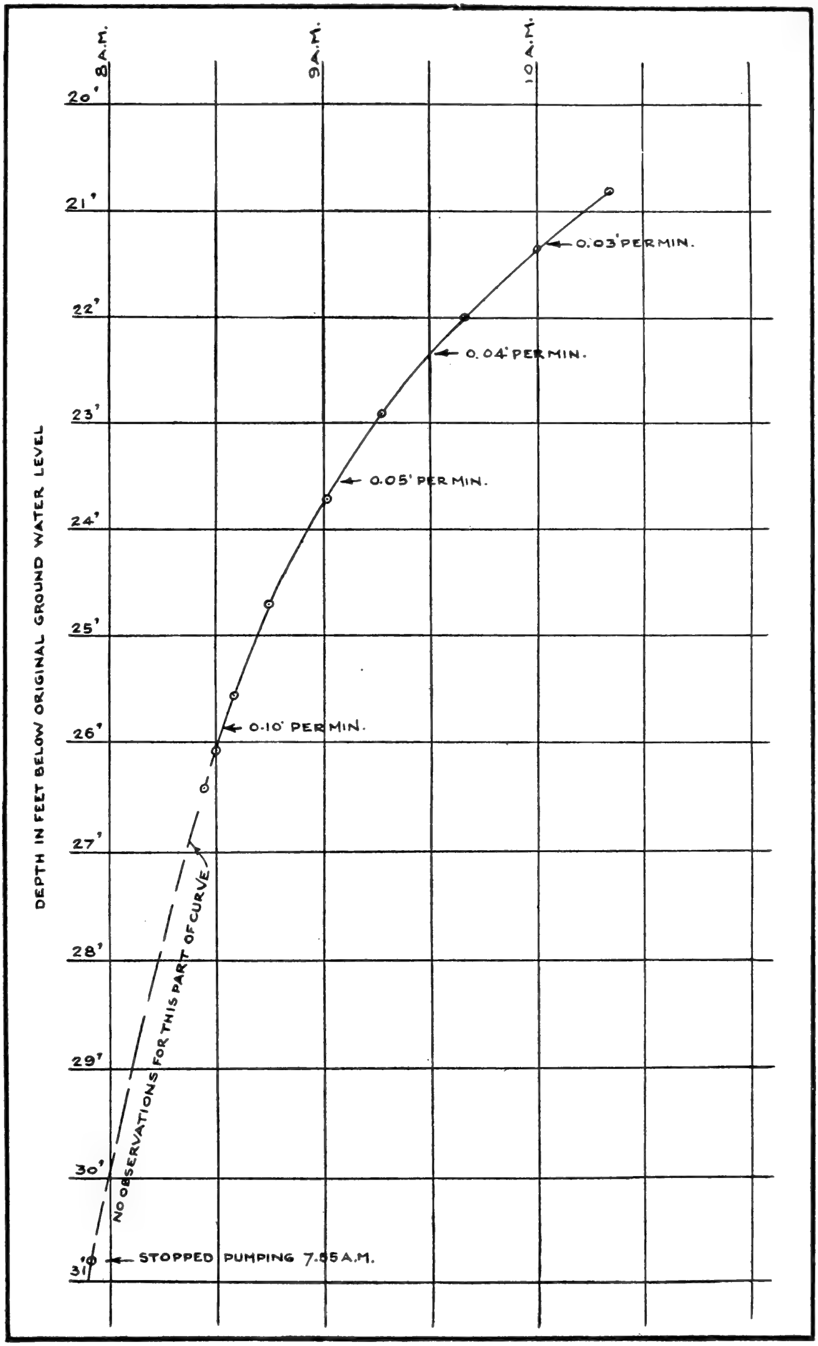


Fig. 25 Curve showing rate of rise of ground water — after pumping — hole 34

three days after pumping ceased water rose 5.2 feet, and in 22 days rose 9.8 feet or at the rate of 0.45 feet per day.

During construction[1] shaft 4 located at same point as hole 32/22, station 607 + 50, has proved a very wet shaft, the inflow varying from 400 to 850 gallons per minute. Pumping at this shaft has lowered the general water level and correspondingly lowered the water level in hole 34/22 at station 600 + 00.

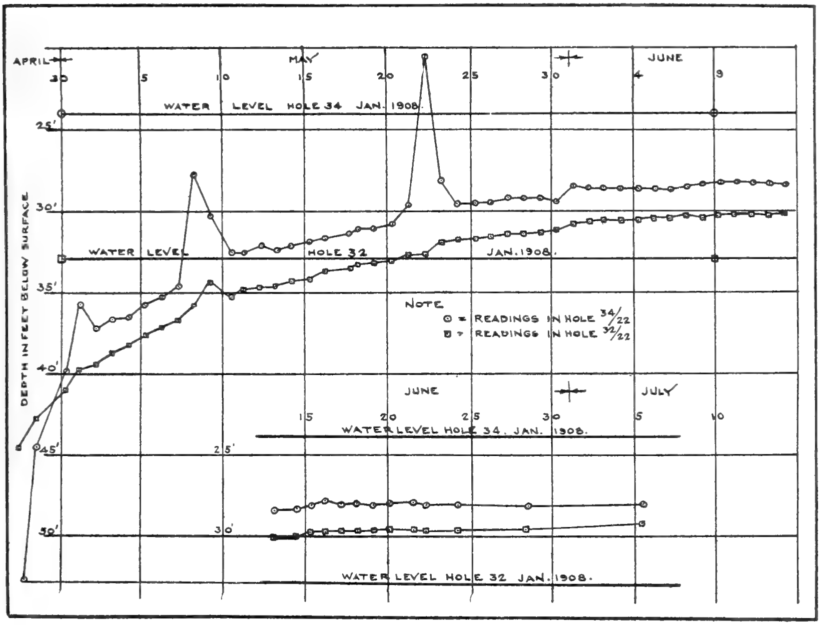


Fig. 26 Curve showing rise of water in holes 32 and 34 after pumping ceased in hole 34

[1] From this shaft after reaching tunnel grade,— 250 feet, and after running northward into the fault zone and porous shales, the contractors are pumping 1300 gallons per minute.

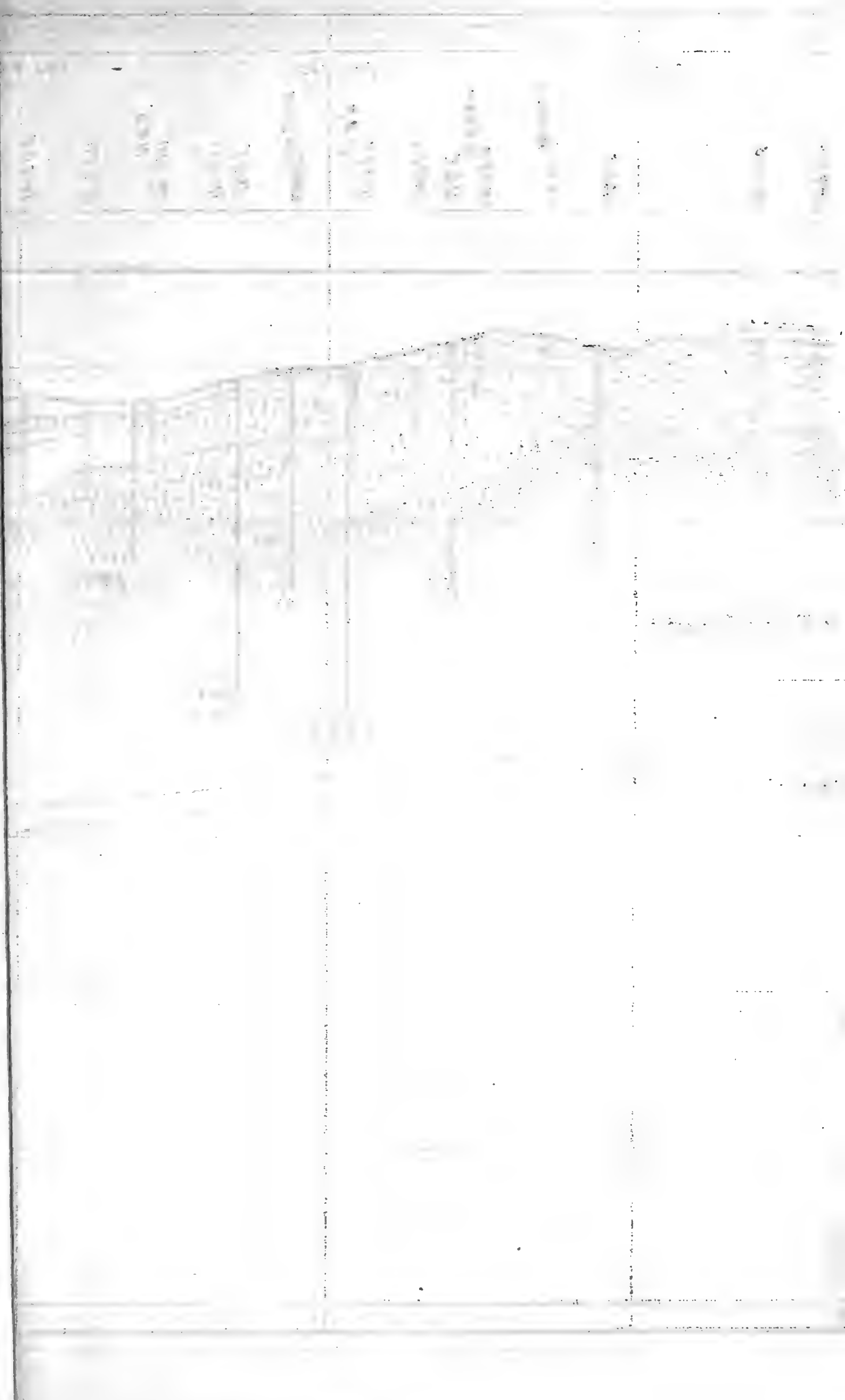
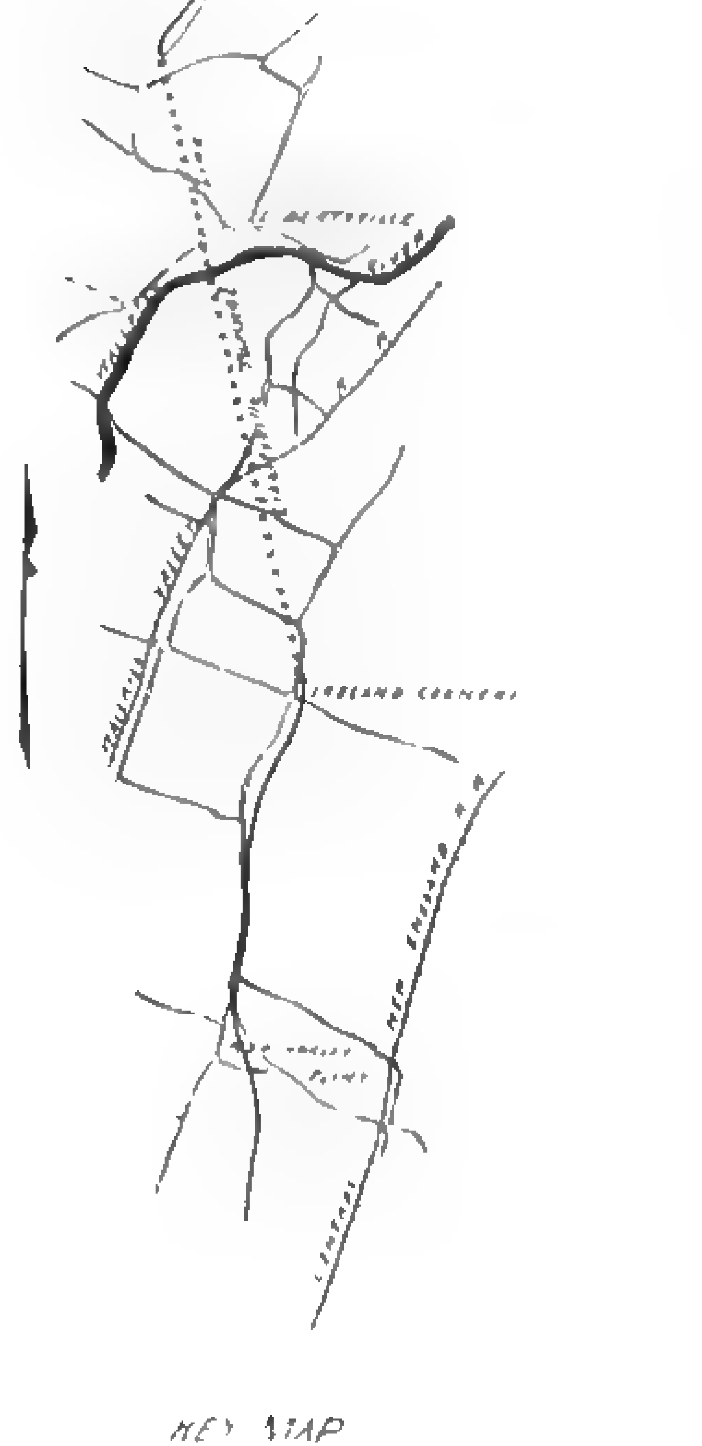


Fig. 27. Profile and geologic cross section of the Wallkill valley from the Shawangunk mountain range to the hills divide near Ireland Corners on the east side of the valley. The exploratory borings are represented, there is an attempt to classify the drift variety, and the approximate position of the pressure tunnel to be constructed for the Catskill aqueduct is indicated.
(Adapted from drawings of the Board of Water Supply)



CHAPTER VII

THE WALLKILL VALLEY SECTION

Between the Rondout and Wallkill valleys the aqueduct is to follow a tunnel at hydraulic grade which so far as can be seen will cut only Shawangunk conglomerate and Hudson River slates. No doubt there are many complicated small structures which because of the nature of the slates can not be reconstructed. The work of tunneling is not advanced far enough to add anything. But in the Wallkill valley, where it is necessary again to plan a pressure tunnel several hundred feet below grade, a considerable amount of exploration has been carried on.[1]

These explorations [*see* sketch map fig. 8] are distributed along several lines crossing the valley at intervals between Springtown, about 3 miles north of New Paltz, and Libertyville, which is about an equal distance south.

The geology is simple. Only Hudson River slates form the rock floor, and so far as can be judged no other formation is likely to be cut by the tunnels. There are no doubt many complicated structures, both folds and faults, as indicated by the high dips, but again because of the nature of this rock it is impossible to discriminate closely enough between different beds to determine exact relations. The point of greatest practical importance lies in the fact that the rock is fairly uniform and, although much disturbed is of such nature that crevices and joints or fault zones are almost as impervious as the undisturbed rock. This is because of the tendency of a formation of this composition to heal itself with fine, compact clay gouge. In fact, the mechanical disturbance produces or develops the cement filling contemporaneously with the movement. It is chiefly a mechanical filling, whereas the healing of a harder and more brittle rock like a granite or a limestone requires more chemical assistance.

An additional practical question involves the estimate of depth required to avoid any possible buried Prepleistocene gorges and maintain a safe cover to guard against undue leakage or rupture.

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[1] Explorations on the Wallkill division are carried on under the direction of Lawrence C. Brink, division engineer. The final construction is in charge of James F. Sanborn, division engineer, with headquarters at New Paltz, N. Y.

To this end most of the explorations were made. Two lines less than a mile apart on which a few exploratory borings were made near Springtown indicate two buried channels, a master channel and a tributary from the west which converge northward. A maximum depth reaching 70 feet below sea level was found on the more northerly line almost directly beneath the present stream channel which flows on drift at an elevation of 150 above tide.

The more southerly profile reaches only sea level indicating a gradient for the preglacial stream at this immediate locality of more than 79 feet per mile.

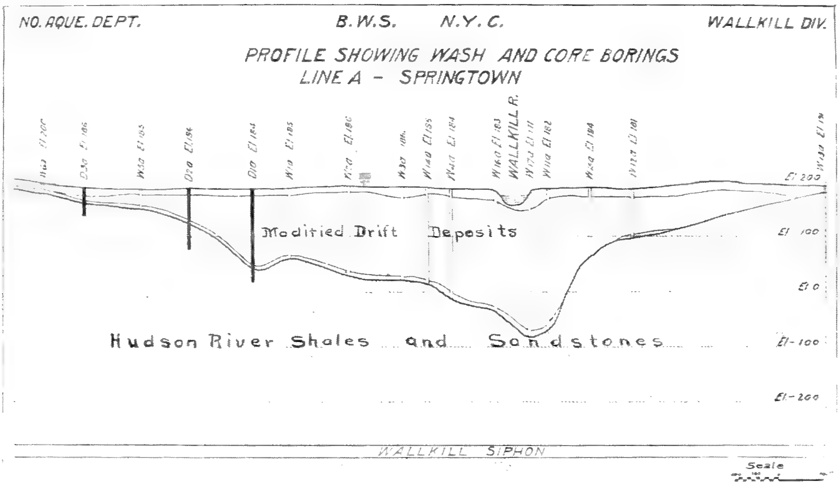
In the vicinity of Libertyville, 5 to 6 miles farther south, where the aqueduct was finally located, the profile was found to be considerably higher. Intermediate profiles are shown in accompanying figures. The deepest point yet found on the Libertyville line is 65 feet above sea level. It is worth noting that the gradient of the ancient Wallkill is therefore shown to be decidedly unsymmetrical. The rock floor formation remains the same although it may vary somewhat in character. Under these circumstances, however, a gradient of 13 feet per mile from Libertyville to Springtown forms a sharp contrast with the 79 feet per mile represented at the Springtown locality. In view of the remarkable increase of gradient and the narrower form it seems reasonable to regard this as a rejuvenation feature developed at the time of extreme continental elevation.

How much deeper the lower Wallkill may be, including the so called Rondout river, which is really a continuation of the ancient Wallkill and geologically belongs to this drainage line instead of to the Rondout, no one can tell. But it is at least interesting to observe that the intervening distance from Springtown to the Hudson at Kingston is approximately 12 miles and that a gradient for that distance equal to the average known in the 6 miles explored, i. e. 24 feet per mile, would depress the outlet 288 feet more. That would be equivalent to 367 feet below sea level. If, however, a steep gradient such as that at Springtown prevails in this lower portion it is necessarily much lower — for example if a 79 foot gradient is maintained it would be possible to reach a final outlet at —1029 feet. It is likely that an intermediate value is more nearly correct. This has, however, an important bearing upon the question of maximum Hudson river depth, especially the existence of an inner deeper gorge above the Highlands. So far as this Wallkill profile goes, it supports the gorge theory. It is certain that the Prepleistocene Wallkill flowed north not very dif-

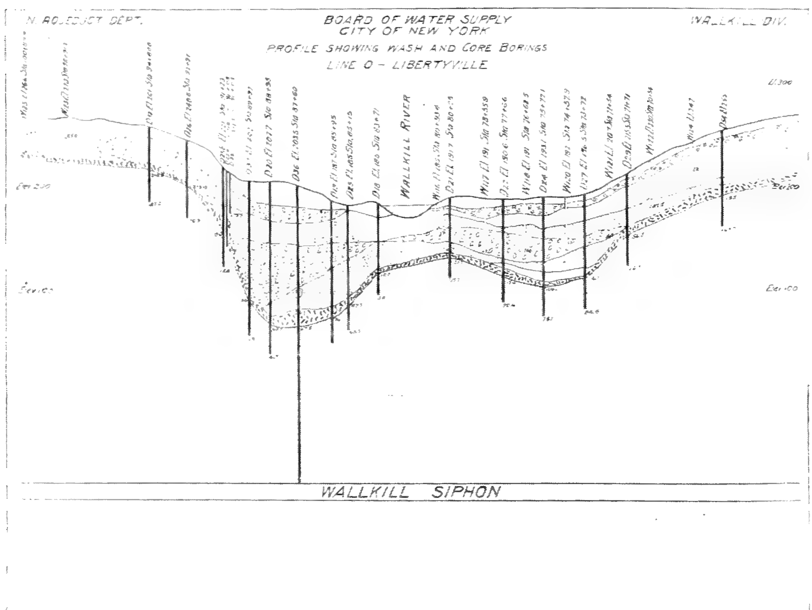
Plate 25

The Wallkill valley looking toward Bronticou Crag in the Shawangunk mountain range. (Photograph by Board of Water Supply)

Plate 25



Cross section showing the buried preglacial Wallkill channel as indicated by exploratory borings near Springtown



Profiles of the present and preglacial Wallkill channels near Libertyville, and a diagrammatic section showing the different types of drift-filling together with the borings which furnished the data

ferently from the present stream except on a steeper gradient, but in all probability the headwater supplies between this stream and the Moodna have been somewhat shifted. It is possible that some former Moodna drainage area is now tributary to the Wallkill. But these changes were wholly glacial in origin and the extent of such shift is indeterminate at present.

It is a notable fact that a large proportion of the work of exploration in this valley was done successfully by the wash rig.

The extensive lot of data was gathered without much delay or difficulty. This is because of the nature and origin of the drift cover. A considerable proportion of the drift mantle especially in central and deeper portion of the valley is modified assorted sands, gravels and silts or muds. In part they represent deposits in standing water laid down at a time when the lower (north) end of the valley was obstructed by ice and while waste was poured into the valley from neighboring ice fields. It is impossible to reconstruct the beds of these materials with any degree of accuracy. But it is at least certain that lens or wedgelike layers of different quality of material were penetrated, indicating oscillation and overlapping of deposition conditions, boulder beds and till being interlocked with assorted sands and gravels. But there is apparently no evidence of ice deposits of greatly differing age. The accompanying profile and cross section is a representation of materials on the Libertyville line based upon identifications made by the inspector of the Board of Water Supply of the Wallkill Division under Mr L. C. Brink, division engineer.

CHAPTER VIII

ANCIENT MOODNA VALLEY

Moodna creek enters the Hudson from the west between Cornwall and Newburgh not more than a mile north of the entrance to the Highlands. It is a retrograde stream in its backward flow similar to the Wallkill. But its channel at present is almost wholly on glacial drift which it has trenched to a depth of more than 100 feet below the average adjacent surface. How much of its retrograde course therefore may be postglacial is not so clear. It seems necessary, however, to account for all drainage on the north margin of the Highlands by streams flowing to the Hudson northward. There is no notch low enough for their escape elsewhere. The ancient Moodna must have carried most of this run-off from the district occupying the angle between the Wallkill and the Highlands. This stream may have drained even more of the region now forming the divide with the Wallkill than does the present Moodna. In any case it must have been a stream of considerable size, capable of excavating a valley or gorge of greater prominence during the period of early Pleistocene rejuvenation than now appears. Furthermore its position makes it highly probable that tributaries of fair size entering in its lower course were also effective enough to require consideration. This conclusion has led to the exploration of the Moodna valley in considerable detail in preparation for the aqueduct work.

The Catskill aqueduct is to cross the stream near Firth Cliffe, which lies almost directly west of Cornwall-on-Hudson, and because of the low surface elevation across this valley, as in the others, a pressure tunnel in rock is judged to be the most suitable type of structure. The accompanying sketch map shows the location.

Explorations were conducted especially for the buried channels and character of rock floor.

Geologic features

The region is one of chiefly Hudson River slate. But there are inliers of the older rocks such as Snake hill which belongs to a long ridge of Precambric gneiss and granite, brought to the surface by folding and faulting and there are more rarely outliers of younger formations such as Skunnemunk mountain. Farther north

at Newburgh a gneiss ridge is accompanied by limestone, but in its southerly extension the slates are in direct contact. This relation is believed to be wholly due to faulting on both limbs of the anticlines. This gneiss ridge disappears southward beneath the drift, but the borings have shown that it continues across the aqueduct line, although it has lost its influence on the topography. There are other inliers of similar character such as Cronomer hill 3 miles northwest of Newburgh. Between these two gneiss ridges lies the southerly extension of the Wappinger limestone belt. But so far as is known it disappears beneath the Hudson River series long before reaching the line of exploration.

Near Idlewild station, filling the space between the two branches of the Erie Railroad, there is a syncline containing the series of Siluric and Devonic strata which spreads southwestward to include Skunnemunk mountain, an outlier of Devonic strata. This is the only occurrence of these formations in this region south of the Rondout valley. The structure and stratigraphic features of this occurrence have been worked out by Hartnagel. Its northward extension in all probability terminates abruptly by a cross fault not far north of the Ontario and Western Railroad.

From these occurrences southward to the Highlands proper nearly everything to be seen through the drift is Hudson River slates.

The Highland gneisses are bounded on the north side by a fault or series of faults. This brings various members of the overlying series into contact along the margin. In the best place where a direct observation can be made the gneisses are thrust over upon the Hudson River slates along a plane that dips about 40 degrees to the northeast. It is probable that a displacement of as much as 2000 feet or more could reasonably be assumed at this place. The contact zone also is much crushed and bears every evidence of having undergone extensive disturbance of this kind. Others of this same type occur within the gneisses where weaknesses formed in this way permit the development of such notches as Pagenstechers gorge. In some cases the rock beneath the surface in these zones is more decayed and less substantial than that at the surface.

Exploration

The first borings made with the wash rig were found extremely unreliable in the Moodna valley. That is because of the very heavy bouldery drift forming the greater part of the filling on the ancient topography. Next to the Hudson river gorge itself, no

place has presented greater difficulties in penetrating this drift mantle. Boulders of such immense size occur that they have to be drilled like bed rock. In one of the holes a boulder 30 feet through was penetrated and 100 feet more of drift found below. Progress in such ground is extremely slow and costly. This is so much the more so where as in this case there are long stretches with unusually deep cover.

A glance at the accompanying profile and cross section will show a very deep and wide valley. Many of the borings are more than 300 feet in drift which almost wholly obscures the ancient topography. The present Moodna is about half as deep and occupies the extreme eastern margin of the older gorge. There is a secondary gorge on the west separated from the main channel by a sharp divide. A few other smaller notches in the line represent smaller tributary or independent stream courses. One of these of much interest is known as Pagenstechers gorge.

The rock floor at all points except two in the central Moodna valley including its two nearest tributaries is Hudson River shales, slates and sandstones of considerable variation, sometimes much brecciated. The two exceptional borings are no. 8/A44 and no. 16/A44 on the west flank of the westerly tributary gorge, and they are in pegmatite and granitic gneiss which is in all probability the narrow southerly extension of the Snake hill ridge. Here again neither quartzite nor limestone were found on the flank, a condition that seems to support the view of a double fault along the Snake hill ridge.

In striking contrast with the broad central Moodna are the two narrow and very deep notches farther to the east, the first in slates and the second (Pagenstechers) in Highlands gneiss.

Special features

Course of the Moodna. The chief interest centers around the Moodna channel. There are several unusual conditions, for example:

The rock floor along the profile is almost flat for a distance of nearly half a mile in spite of the fact that there would seem to be every reason for a different form. The differences in hardness of rock floor alone would encourage differential erosion; and, since the structure of the formations, the strike, is almost parallel to the supposed course of the stream, the influence of different beds would be at a maximum. Furthermore, the deep gorge of the Hudson, into which the stream flowed is only 2 miles away;

and if that gorge represents stream erosion to such depth (over 750 feet) it would indicate a gradient of nearly 300 feet to the mile for the last 2 miles of the Moodna — a condition to say the least decidedly unfavorable to the development of a flat-bottomed valley.

Of course, if the profile as determined can be assumed to run exactly parallel to the old stream channel for half a mile it would be less surprising. But even then it is too flat. For so short a distance from the Hudson gorge the gradient ought to be much greater than the variation observed in the Moodna channel. There are certainly reasons in the structural geology favoring a northeast course instead of one parallel to the profile line. And if the stream really did flow across this structure, the differences of hardness of beds ought to have encouraged a much greater difference in depth of channel than the profile presents. With structures all running northeast there is every reason to expect the stream to follow them.

Recent exploratory data strongly supports the theory that the Hudson gorge at Storm King gap is widened and possibly somewhat overdeepened by glacial ice. Under normal stream relations one might consider the Moodna a tributary hanging valley, itself rounded and smoothed to a broad U-shape by ice. This would be a very easy solution if it were not for the fact that this tributary Moodna opens into the Hudson as a reversed stream, i. e. it opens against the flow of the Hudson and more or less directly against the known ice movement. It can not be a hanging valley therefore of the normal sort. If a hanging valley of ice origin at all it would necessarily be one therefore gouged out by ice moving from its mouth toward its head, a case that so far as the writer knows has never been observed. The chief objection to this theory is that in no other gorge or channel (with one exception, the Hudson at Storm King gap) anywhere in the region so far as known is there any evidence of serious modification of an original stream channel by the ice invasion. Of course, the axis of the valley is favorable and the situation is peculiar in that it parallels the Highlands front in this vicinity and the action of the ice may be assumed to have been somewhat concentrated along this margin because of the obstruction.

Inner notch or secondary gorge. Those who habitually emphasize ice action would no doubt choose to regard this whole valley as shown in the profile, as chiefly glacial in character and origin. If that explanation is the true one, then it must be admitted that a deeper smaller inner notch or gorge is unnecessary and indeed unlikely.

The critical point therefore in the whole argument is as to the origin of the valley, i. e. is it essentially a stream valley? Or is it as to present rock floor form wholly a glacial valley?

If it is a stream valley then no doubt full account must be taken of the proximity to the Hudson, and the possibility of developing a temporary graded condition and some adequate allowance must be made for its work during the subsequent continental elevation and the deepening of that river to several hundred feet below the known bottom of the Moodna. In short, one would expect a narrow deeper notch in the Moodna floor as a result of this rejuvenation. But on the contrary if in preglacial time the stream were not so powerful and had not been able to keep pace, and if the ice movement can be assumed to have concentrated along this line to such efficiency as to gouge out a groove 3000 feet wide almost flat to a depth of 300 feet only guided in direction by the original Moodna, then one may readily abandon the idea of a deeper notch.

One or the other of these types of origin must be the chief factor in reaching a reasonable opinion as to the presence of an inner notch.

In any attempt to choose between these factors, one is led to reconstruct the preglacial drainage lines. When this is done it at once appears as most probable that there was at that time as now a considerable area tributary to the Hudson with a stream course very much like the present Moodna. In other words a fair sized stream is assured. Once such a stream is granted and the effects of its work reckoned in full knowledge of the adjacent Hudson, and its probable behavior is studied in the light of the data obtained in exploration of the valleys of other tributaries, it becomes more and more difficult to wholly eliminate the inner gorge idea. It seems to the writer probable that the valley owes its erosion chiefly to the preglacial stream. But the channel has suffered subsequent widening and smoothing by ice especially in its upper and broader portion, below which there may yet be a notch. One must admit that the results of boring prove the notch to be very narrow, less than 150 feet, or else not there at all. In reaching an opinion as to the possibility of one so narrow, it is worth while to note that the Esopus, which is a larger stream, has cut down at Cathedral gorge to a depth of from 50 to 80 feet with almost vertical sides and only about 150 feet wide. This gorge furthermore is cut in almost horizontal strata of such character that there is no special structural tendency in them to contract the stream. At the Moodna on the contrary, in addition to the smaller

size of stream, the rocks stand on edge and run parallel to the supposed course so that this structural influence is toward a narrow and reasonably straight gorgelike form. It is not only possible that the gorge is narrow, but even probable that it is narrower than the present Moodna, i. e. less than 100 feet wide.

How deep such an inner gorge may be if it does exist is a practical question in this particular case, because its depth has a direct influence on choice of depth of pressure tunnel. Because of the evident narrowness it is likely that it is not of very great depth — in view of the quality of these shales perhaps not over a hundred feet.

Is there any one point more than another favorable for such a notch? There are two facts bearing on this question, (1) the variation in core saving which indicates that hole no. 5/A44 with 7% has a recovery of only 1/5 the average, and (2) the fact that hole no. 15/A44+, which is the next hole, shows the lowest bed rock in this valley. On the ground of profile therefore and on the ground of structural weakness there is reason to choose this space between no. 5/A44 and no. 15/A44 as the most likely position.

Summary. The very abnormal profile of the Moodna valley based upon the borings may be due either (1) to parallelism with the stream course, or (2) to a graded condition of the stream in some preglacial epoch, or (3) to modification of an original less prominent channel by ice erosion.

It is the opinion of the writer that the ancient stream crossed the profile line much as the present stream does, that the additional narrower valley immediately to the west side is that of a preglacial tributary instead of a bend of the Moodna itself, that there was a development of a moderate sized somewhat flattened valley corresponding to the benches and shelves noted in other streams, including the Hudson, that subsequent elevation of the continent rejuvenated the stream which cut a deeper narrow inner notch, that glacial ice moving in reverse direction widened and smoothed this upper portion of the valley, but that there may yet be a remnant of the deeper notch in its bottom, and that the space between holes no. 5/A44 and no. 15/A44 is the most likely location of this inner gorge.

Tributary divide. The sharp divide between the two deep portions of the valley bottom has proven an evasive feature in the later exploration. Two holes put down a short distance to the southward (24/A44 and 20/A44) failed to find the rock floor so high, one reaching rock at a depth of 181 feet and the other failing


STORM KING MT.
LITTLE ROUND TOP
SHAFT
A
B
C
D
E
F
Moodna Creek
VAILSGATE
ERIE R.R.
REILLY'S RIDGE
Granite
Fault
Slate
PROFILE ALONG LINE A-B
Glacial Drift
Granite
Fault
PROFILE ALONG LINE C-D-E-F
GEOLOGIC SECTION OF MOODNA CREEK VALLEY
SCALES
HOR. 1000'
VERT. 200
300
200
100
0
-100
-200

to find rock even at 213 feet. Two others nearly a thousand feet to the westward, however, found rock again at approximately the same elevation as the divide. If this is a tributary stream divide therefore it must have an east-west trend.

Pagenstechers gorge

This is a notch between Storm King ridge and Little Round top occupied by a very small mountain stream. The rock floor is granite gneiss of the Storm King type. Its special characters are (1) extreme shattering or crushed condition, and (2) extensive decay along this zone which has softened the rock constituents to great depth.

Considering the nature of the granite gneiss in general this narrow gorge is a surprisingly deep one. But this is no doubt due to the influence of the decayed crush zone. The drill cores taken from the holes that penetrated the floor at this place are so much altered that, after several months exposure to the air, they can be readily crushed in the hand. Hole no. 16/A45 which is centrally located penetrated to —196 feet. It is in material of this same condition, to at least — 100 feet. Similar conditions are proven to the north of the line, shown in the accompanying profile and a rapid increase in depths. From the surface outcrops farther up the gulch it is easy to see that the crushed zone extends in that direction with the strongest lines about s. 70 w. This is doubtless on the strike of the fault lines of the northern border of the range. It is of more than usual interest in showing the depth to which incipient decay has penetrated in these crush zones, and the efficiency of stream erosion along them.

Overthrust fault

The principal fault line follows the margin of the granite gneisses. At the best exposure of it the Hudson River slates are overridden by the gneiss. This represents therefore the cutting out entirely of the Wappinger limestone and the Poughquag quartzite and a part of the slates by the displacement which must amount to at least 2000 feet and probably more. The same relation is indicated by the borings and by the outcrop near the village of Cornwall, but a little limestone is found midway between the two points along the strike of the fault. The strike of the fault averages about n. 65° to 70° e., but locally, at the best exposure, it is only n. 35° e. The dip is southeast at an angle of approximately 45 degrees.

Statistics

Moodna valley

I HOLES BORED UNDER AGREEMENT NO. 18

No. A18	Surface elevation in feet	Rock elevation in feet	Rock penetration in feet	Per cent core saved	KIND OF ROCK
1	86	+27	22	0	Slate and sandstone

(On porosity test with plug at 58 feet deep the loss of water was 6 gallons per minute with pressure of 0–10 pounds per square inch.) Test unsatisfactory because of large hole.

No. A18	Surface elevation in feet	Rock elevation in feet	Rock penetration in feet	Per cent core saved	KIND OF ROCK
2	236.5	?	0	0	0
3	136.3	36.7	26	0	Slate

(On porosity test with depth to plug 173.5 feet and pressure 0–60 pounds per square inch the loss was 5 gallons per minute.) Test unsatisfactory because of large hole.

No. A18	Surface elevation in feet	Rock elevation in feet	Rock penetration in feet	Per cent core saved	KIND OF ROCK
4	259.6	39.4	154.5	75	Slate and sandstone
5	295.5	37.5	129.2	71	Slate and sandstone
6	302.7	?	0	0	0
7	297.0	+26	30.7	0	Slate

2 HOLES BORED UNDER AGREEMENT NO. 40

No. A40	Surface elevation in feet	Rock elevation in feet	Rock penetration in feet	Per cent core saved[1]	KIND OF ROCK
1	276	201	125	0	Slate
2	274.3	228.8	52.5	0	"
3	294.7	257.7	45.3	0	"
4	273.1	222.1	139.7	60	Slate and sandstone
5	347.1	239.1	48.7	0	Slate
6	374.6	250.6	38.0	0	"
7	168.4	40.4	110.1	88	Slate and sandstone
8	188.7	168.2	325	76	Slate and sandstone
9	176.3	164.3	25.5	0	Slate
10	172.3	46.3	26	0	"
11	169.9	98.9	25.5	0	"
12	221.2	208.2	25.5	0	Slate and sandstone
13	226.7	210.7	32.7	0	"
14	226.6	212.6	31.0	0	"
15	230.1	215.1	32.5	0	Slate and sandstone
16	208.3	184.3	32.0	0	Slate
17	169.2	43.2	25.0	0	"

[1] In cases which show no recovery of core a method of drilling was employed different from the others and the rock was ground to pieces. Failure to recover core may therefore be no indication of poor rock quality.

3 HOLES BORED UNDER AGREEMENT NO. 44

No. A44	Surface elevation in feet	Rock elevation in feet	Rock penetration in feet	Per cent core saved	Kind of rock
[1]1	313.6	—17.4	167.5	15	Slate and sandstone
[1]2	274.5	+171.5	229.6	20	Slate and sandstone
3	282.7	+39.7	58.8	14	Slate
4	277.8	—22.2	166.7	26	Slate and sandstone
5	299.5	—47.0	50.9	7	Slate and sandstone
6	279.5	—40.3	43.0	27	Slate
7	299.2	—51.6	102.2	27	Slate
8	277.	+89.0	109.3	57.6	Granite gneiss and quartz
9	282.6	+7.6	90.	13	Slate and sandstone
10	230.5	—39.5	154.7	49	Slate and sandstone
11	249.5	—32.5	93.5	11	Slate and sandstone
12	272.0	—45.	58.6	30	Slate and sandstone
13	288.4	—37.6	79.0	13	Slate
14	185.1	—39.9	91.8	32	Slate and sandstone
15	301.8	—59.2	75.	45	Slate and sandstone
16	277.3	+25.9	104.6	43	Pegmatitic granite
17	300.	—42.	75.2	33	Slate and sandstone

[1] Porosity test made on hole no. 1 shows a loss of .03 gallons of water under 100 pounds pressure with packer at depth of 387 feet. Depth to ground water 217 feet.

Porosity test on hole 2/A44.
Ground water level at a depth of 90 feet = el. + 184.5′.

SUMMARY

Depth to packing in feet	0 40	20 60	40 80	60 100	80 120	100 = Gage pressure 140 = Calculated pressure[1]
146	.25	.37	.50	.64	.79	1.03 = gallons lost
196	.20	.27	.35	.42	.52	.67 "
247	.09	.12	.16	.19	.23	.28 "

[1]Calculated pressure equals average pressure plus weight of column of water from surface to ground water level. Gage pressure is given in pounds per square inch. Loss is in gallons per minute.

4 HOLES BORED UNDER AGREEMENT NO. 45

No. A45	Surface elevation in feet	Rock elevation in feet	Rock penetration in feet	Per cent core saved	Kind of rock
1a	426.2	278.4	19.7	0	Slate with quartz
2	390.5	266.5	76.	0	Slate
3	442.8	286.8	25.5	0	"
4	432.9	268.9	31.	0	"
5	433.	307.5	36.5	0	"
6	180.1	161.8	81.7	53	Slate with quartz
7	179.4	163.4	26.0	0	Slate
8	214.2	142.2	46.5	0	Decayed granite gneiss
9	179.4	151.9	27.5	0	Slate
10	260.1	237.1	34.0	0	"
11	214.6	155.6	95.5	0	Decayed granite gneiss
12	237.6	236.6	35.5	0	Slate
13	182.7	168.6	287.4	48	"
14	269.8	257.3	28.	0	"
15	209.6	130.1	36.1	0	Decayed granite gneiss
16	213.2	11.7	308.3	28	Decayed granite gneiss and seamy gneiss
17	387.6	387.6	163.0	69	Gneiss and dyke rock

CHAPTER IX

ROCK CONDITION AT FOUNDRY BROOK[1]

Foundry brook is a small stream entering the Hudson at Cold Spring in the Highlands. It drains a rather abnormally large valley bordering Bull mountain, and Breakneck ridge on the east, and its axis is in the strike of the principal structure of the gneisses which form the chief rock formation of the floor. This valley is in exact line with the course of the Hudson from West Point immediately southward, and its rock formations are similar in character and condition.

There is greater variety of rock composition in this belt, i. e. the Foundry Brook–Hudson river belt, than in any other in the Highlands of similar area. The eastern half of the belt is a typical development of banded gneisses and schists and quartzites belonging to the sedimentary representatives of the Highlands gneiss. Small layers of interbedded limestones are frequent together with serpentine, and mica and graphite and quartz schists. In addition along the east bank of the Hudson, they are profoundly modified by crushing and shearing in zones that trend with the formation, i. e. in a direction leading toward and through Foundry brook valley.

The west side is much less variable and is bounded at the margin by one of the most massive types of the region — the Bull mountain and Breakneck mountain gneissoid granites, which are essentially the same as that of Storm King mountain.

But additional structures enter Foundry brook valley from the western side at an acute angle with its axis and formational trend. These additional structures are two well marked faults, which cross the Hudson — one along the precipitous southeast face of Crows Nest and the other along the southeast face of Storm King mountain. These are the most pronounced escarpments of the whole region. The first one crosses the Hudson between Cold Spring and Bull mountain and in passing northeastward loses much of its influence upon topography and its movement is probably dissipated in that direction. A line from the southeastern face of Crows Nest to the point to be described runs n. 50° e.

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[1] Explorations at Foundry brook were done under the direction of Mr William E. Swift, division engineer, now in charge of the Hudson River division of the Northern aqueduct.

Explorations

Foundry brook therefore contains structures that could produce considerable effect upon the quality and condition of rock floor. The rock floor is covered with heavy bouldery drift—thicker on the Bull mountain flank than in the valley bottom proper. Where the aqueduct line crosses the floor is at an elevation of 200 feet to 350 feet A. T. Hydraulic grade of the aqueduct is about 400 feet.

The lowest bed rock found along the line is 182.3 feet and the channel of the present stream coincides with the preglacial one in that portion of its course. There are two secondary channels — probably tributary stream channels on the west side. One of these lies under 70–80 feet of drift.

Borings were made for the purpose of determining the rock floor profile and the condition of bed rock. In most of them the ordinary gneisses and granites were penetrated in normal condition.

But in a few a very unusual condition was found. Hole no. 2 at el. 347 feet near the west or Bull mountain margin penetrated 49 feet of drift to el. 298. Then the drill passed into gneiss which was at the top, the first 30 feet, of a fair quality. This is shown by the core recovered — the first 12 feet recovering over 50%. But the percentage of recovery rapidly fell off — amounting to only 36% in the first 50 feet. Only 1 foot of core was recovered in the next 30 feet, or only 3%. While from that point el. 220 feet to the bottom of the hole el. 51.8, at a depth of 295.7 feet from the surface, nothing but fine decomposed matter was washed up. There was no core at all. This was at first reported as sand by the drillmen, and, coming at a time when exploration of deep buried gorges was the rule at other points of the aqueduct, there were many questions about the interpretation of this new hole, the first assumption of the drillers being that an overhanging ledge of a very deep gorge had been penetrated passing through it into river sands below. A little study of the material proved that this view is untenable. The sandy wash from the drill is true disintegrated gneiss much decayed and dislodged by the drill.

But the meaning of it and the extent of it are after all important additional questions.

Interpretation and further explorations

It is certain that the soft material and the "sand" reported from this boring represent rock decay induced by underground water circulation. Water circulation is rather free as is shown by the

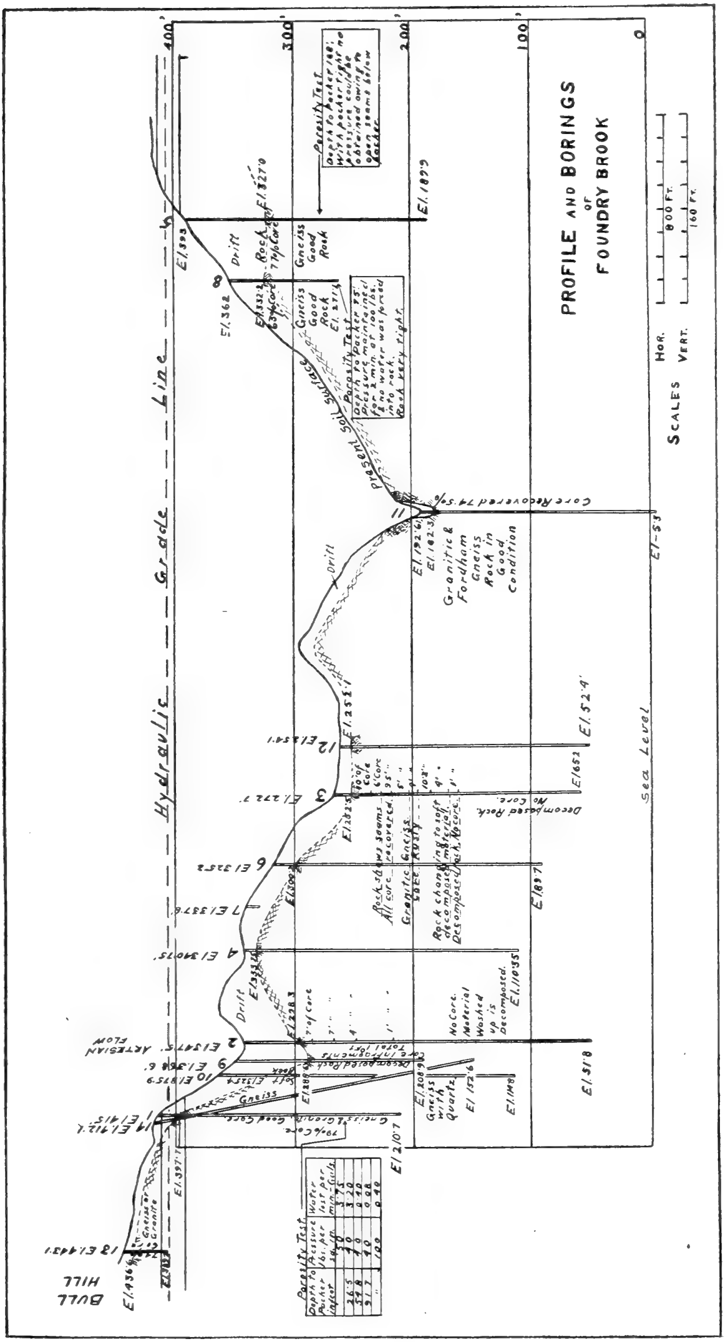


Fig. 29 Structural detail of Foundry brook valley as indicated by borings.

fact that there was an artesian flow from this hole of 10 gallons per minute after reaching a depth of 80 feet, which increased to 15 gallons per minute after reaching a depth of 253 feet. This underground supply is maintained since completion and the pressure is sufficient to raise the water about 15 feet above the surface.

This is a behavior that is consistent with the geologic conditions. The boring has no doubt penetrated a crush zone following one of the faults which enters this side of the valley. The crush zone dips steeply and the boring has penetrated the hanging wall of more solid rock in the first 50 feet and, after reaching the broken and decayed portion of the zone, has swung off parallel to the dip and avoiding the more resistant foot wall has followed down on the soft inner streak.

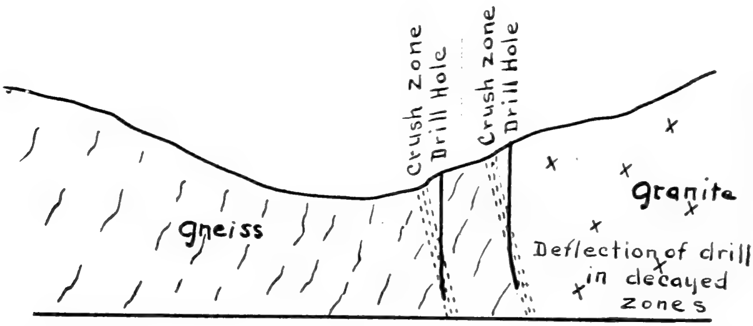


Fig. 30 Sketch illustrating the interpretation of geologic structure across Foundry brook valley indicating the relation of certain borings to them and their supposed influence in deflecting the drills

This crush zone extends on northeastward across higher ground where opportunity for taking in surface water is offered. This is without doubt the source of supply for the circulation which furnishes the artesian flow and which has been so effective in producing decay to great depth. But the circulation and associated decay are probably limited to comparatively narrow zones. There is no good reason for assuming large masses of rotten gneiss at great depth. The worst zones are narrow but may be comparatively deep, i. e. they may extend much deeper than any of the borings yet made in this valley. The depth of decay is related to the outlet for underground circulation which in this case is the gorge of the Hudson.

Several other borings encountered similar conditions, especially those on the west flank of the valley within range of the belt in which the fault seems to be located.

Hole no. 9 reached the rock floor at a depth of 80 feet, and then penetrated rock to a depth of 159.7 feet. All of the material is badly decayed. Only 1 foot of core was recovered from the whole boring and that is mostly quartz coming from a veinlet or pegmatitic streak at 141 feet. Water under slight pressure was encountered in this hole also. But because of the somewhat greater elevation of the surface at this than at hole no. 2 there is not a constant outflow.

Two other holes immediately to the west show much better rock condition — no. 1 showing 79% core recovery. Also two on the east side at greater distance [*see* accompanying profile] show good rock. But one other no. 3 at a distance of over a thousand feet to the east encountered another zone of decayed rock, the record being very similar to no. 2 in that poorer conditions are shown at depth than near the surface. Rock was found at a depth of 20.2 feet. From 20.2 to 116 feet the gneiss was quite hard, 55.3 feet of core being recovered or 57.7%. But from 116 feet to the bottom 207.5 feet the material was as bad as in hole no. 2, and no core was recovered.

Several other tests were made on the borings with a view to determining the character and extent of these features more definitely. For example, if the interpretation given for the behavior of no. 2 and no. 3 is correct it ought to be possible to survey the holes and determine a deflection from the vertical as the drill deviated from its course to follow the softest streak. A survey conducted for this purpose indicates just such a result. The accompanying sketch shows the data plotted. The drill was deflected 4° 36′ at a depth of 50 feet, 7° 36′ at 100 feet, 8° 2′ at 150 feet and 9° 40′ at 198 feet.

Pressure tests were made for porosity on some of the holes in sound rock. Some of these data are given on the profile.

Some of the rock of this valley, if very extensive, such as that in borings no. 2, no. 3 and no. 9, would be very poor ground for tunneling. The practical question involves especially the width of these zones, are they a foot wide or are they a hundred? In an attempt to help settle that question an inclined hole was proposed that was to run at an angle low enough to crosscut these belts. Accordingly hole no. 14 was bored inclined 40° 26′ to the horizontal and started on the solid granite gneiss. The results were not

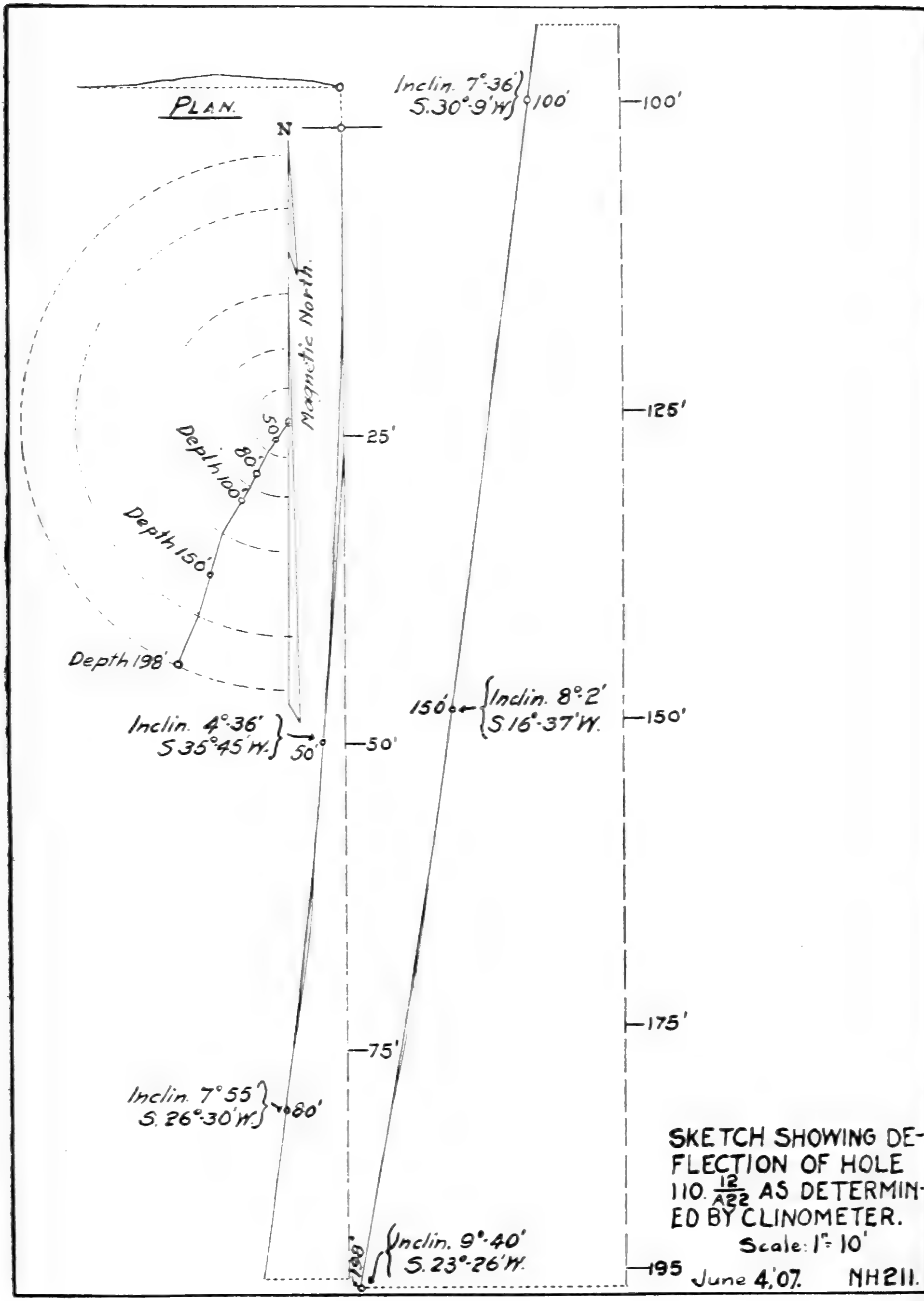

PLAN.
N
Magnetic North.
50'
80'
Depth 100'
Depth 150'
Depth 198'
Inclin. 7°-36'
S. 30°-9' W.
100'
—100'
—125'
—25'
Inclin. 4°-36'
S 35°-45' W.
50'
—50'
150'
Inclin. 8°-2'
S. 16°-37' W.
—150'
—175'
—75'
Inclin. 7° 55
S. 26°-30' W.
80'
Inclin. 9°-40'
S. 23°-26' W.
198'
—195
SKETCH SHOWING DEFLECTION OF HOLE 110. 12/A22 AS DETERMINED BY CLINOMETER.
Scale: 1" = 10'
June 4, '07.
NH211.

Figure 31

very encouraging. The decay is shown not to be confined to mere seams. The doubt raised by so much bad ground has finally led to the adoption of a different plan for crossing Foundry brook valley and no further data are likely to be added by this work. As it now stands the borings at Foundry brook indicate the deepest decay of any yet made in granites or gneisses except those of Pagenstechers gorge on the north side of Storm King mountain. Both cases are of similar origin and history, but Foundry brook is apparently the more complex in occurrence. There are several parallel zones along which there is extensive decay to a depth of more than 300 feet.

CHAPTER X

GEOLOGY OF SPROUT BROOK

Three creeks unite to form an inlet at the sharp bend in the Hudson immediately above Peekskill. The middle one of these is known as Sprout brook. It occupies a deep and narrow valley that is well marked for 10 miles in its lower course and is traceable as a physiographic feature of less prominence to the north margin of the Highlands. Its persistence indicates some important structural control in erosion.

Geology

This valley lies in the midst of the most typical gneisses and granites of the Highlands region. And in addition several of the "iron mines" of Putnam county lie on its western flank. The rocks are complex granitic and quartzose gneisses and granites. Foliation and banding and bedding wherever this appears is parallel to the axis of the valley. The most notable geologic feature is the occurrence of a broad belt of crystalline limestone throughout the lower 4 miles. It is undoubtedly chiefly this limestone, which is less resistant to weather than the gneisses, that controls the form and size of the valley. As to geologic relations, this is one of the most interesting formations of the region. It is coarsely crystalline, full of silicious impurities at many places and carries small igneous injections and dykes, and so far as the bedding can be followed, stands almost on edge. Although an actual contact is not seen, at several places the limestone and gneiss approach within a few feet of each other and it is certain that no other formation can come between them. This is more certainly indicated in the northerly extension of the valley where the limestone gradually disappears leaving only the gneisses and granites. That there may be a fault contact must be admitted, but of this there is no good evidence in the field.

Such relations and character show that this limestone is similar to the smaller interbedded occurrences noted frequently with the gneisses in the Highlands and elsewhere. If it is of that type then it is the largest representative yet found in that series. But it is also in these characters similar to the Inwood limestone of more southerly areas. The overlying Manhattan schist which is lacking

may have been removed in erosion. One of these types it resembles, but it can not be the Wappinger (Cambro-Ordovicic) as was pointed out by the writer in a former report.[1] The Wappinger, wherever known to be such, is never intruded and always lies above a thick quartzite (Poughquag). It does so even in the next valley (Peekskill creek) less than a mile distant. With the interpretation of this Sprout Brook limestone therefore is involved the correlation and interpretation of the age of much greater areas. That the Sprout Brook limestone is not Wappinger is clear enough, but it could be either interbedded (Grenville) or Inwood. If it is Grenville then of course it has no direct bearing on the Wappinger-Inwood question and these two might be equivalents. But if the Sprout Brook limestone is not Grenville (interbedded) then it must be Inwood and in that case the Inwood and Wappinger are not equivalent — which means that there are two series above the gneisses instead of one — an Inwood-Manhattan series, and a Poughquag-Wappinger-Hudson River series. At the present time it is not possible to give with certainty a final interpretation of the Sprout Brook limestone.

Explorations [2]

It was at first believed that a pressure tunnel could be constructed advantageously at the point of crossing this valley and borings were made to test rock conditions. The data gathered in exploration are indicated on the accompanying geologic cross section [fig. 32].

Borings indicate that the rock floor has been eroded to a few feet below present sea level and that the gorge has a drift filling of more than 150 feet. The central borings penetrate limestone and indicate a total width of this type of more than 400 and less than 600 feet. The best estimate on the basis of these explorations is 500 feet. Whether this width represents one thickness of the formation as would probably be the case if it is an interbedded Grenville layer, or part of a double thickness due to infolding, as would probably be the case if it is the Inwood, there is no evidence. The thickness seems to be even greater farther south in the same valley (it becomes ¼ mile wide), but it can not be

[1] Structural and Stratigraphic Features of the Basal Gneisses of the Highlands. N. Y. State Mus. Bul. 107 (1907). p. 361–78.

[2] Explorations at Sprout brook are in charge of Mr. A. A. Sproul, division engineer in charge of the Peekskill division.

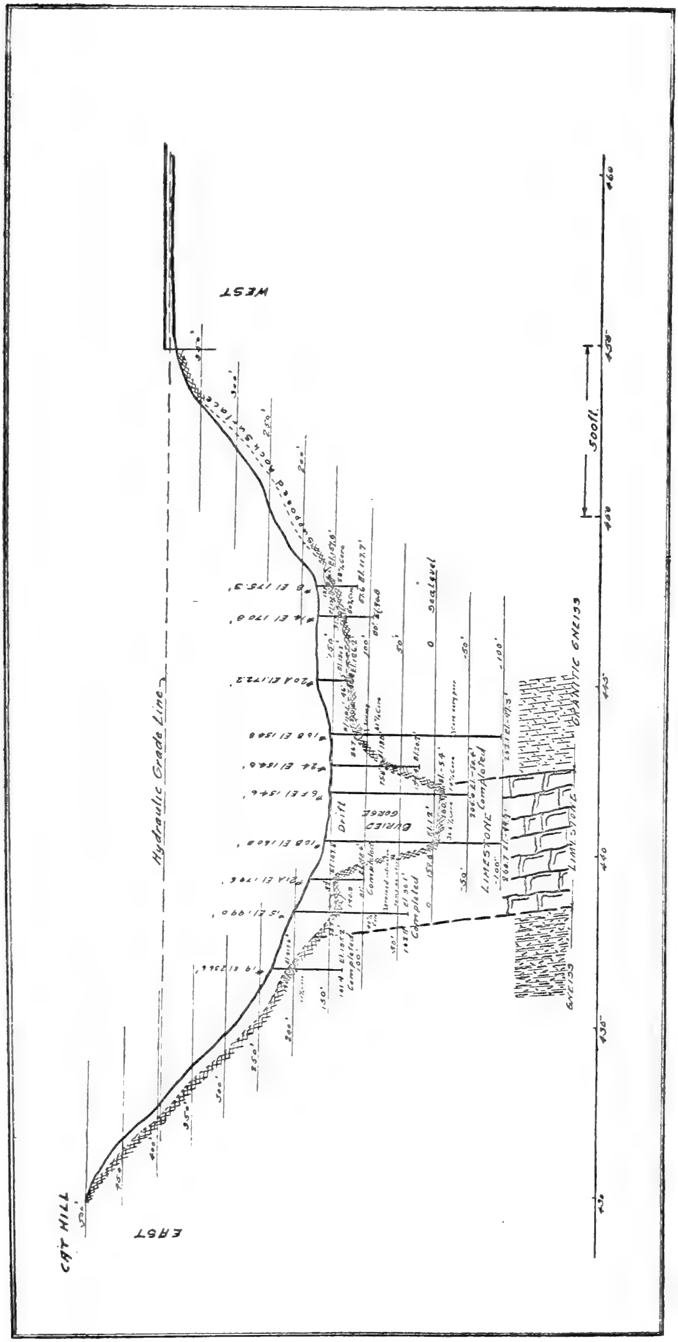


Fig. 32 Geologic cross section of Sprout brook as indicated by the exploratory borings of the Catskill aqueduct

accurately measured and there is no way of guarding against repetition of folds. The valley floor is decidedly terraced at an elevation of about 130 A.T. One side is limestone and the other is granitic rock. This is probably a local mark of the Tertiary base leveling work.

Because of the great depth of this narrow gorge, it would require a 500 foot shaft at each side to lead from hydraulic grade down to a safe level for the pressure tunnel. For a crossing not more than 2000 feet long this is excessive and the cost becomes greater than by other methods of construction. Consequently the tunnel plan has been abandoned and it is not likely that further data bearing upon these questions will be added.

CHAPTER XI

STRUCTURE OF PEEKSKILL CREEK VALLEY

Immediately east of Sprout brook, described in the previous section, is Peekskill creek, which drains the largest valley emerging from the southern margin of the Highlands. This valley as a physiographic feature is continuous with the Hudson river gorge from the sharp bend at Peekskill to Tompkins Cove. There are important structural features along the strike of this valley which extend very far beyond the limits of Peekskill creek itself, among which are strong folding and block faulting. The chief fault continues to the southwest with still greater prominence and appears on the west side of the Hudson in the escarpment forming the southeastern margin of the Highlands continuously for many miles into New Jersey.

Near the Hudson, Peekskill creek and Sprout brook unite and the structures and formations characteristic of each valley converge until in the last half mile of their united course rock formations characteristic of Sprout brook lie on one side of the valley, those characteristic of Peekskill creek on the other, and the contact which follows the divide to that point then passes beneath the waters of Peekskill inlet. Because of the block faulting which has carried down overlying formations and protected them from the total destruction characteristic of the central Highlands region this valley is of unusual interest.

Explorations [1]

The aqueduct line crosses this valley about 3 miles from the Hudson, and in determining the possibility of crossing by pressure tunnel in rock a considerable number of explorations were made.

Enough has been done to outline the rock floor profile very definitely and to determine the condition of the formations.

An examination of the drill cores and records of explorations shows the following facts which are compiled as fully as possible on the accompanying cross section.

Phyllite. One boring (no. 1) is in a phyllite whose character and relation to other formations leads to the conclusion that it

[1] These explorations were directed by Mr A. A. Sproul, division engineer of the Peekskill division with headquarters at Peekskill, N. Y.

belongs to the Hudson River slate series. This type of rock forms the whole western side of the valley for several miles. Beds stand on edge or dip steeply southeastward and are in good sound physical condition. The rock is everywhere a fine grained micaceous slate or phyllite and in some places carries pyrite crystals. It is impossible to estimate the thickness or minor structural habits. But it is clear that it forms the upper member of a series that has a synclinal structure and therefore the belt represented by the phyllite marks the axis of the syncline although the chief valley development lies wholly to one side.

Limestone. Eleven borings (no. 2, 3 D, 4 C, 11, 13 C, 18, 22, 23, 25, 26 and 29) are in limestone. All show essentially a very fine grained close textured crystalline gray or white or bluish rock with strong bedding standing nearly vertical or at very high angles. This, because of its character and relation to other formations, is regarded as the Wappinger limestone — a formation well known north of the Highlands, where it is at least 1000 feet thick. From present explorations it is now certain that a belt 3250 feet wide is underlain continuously by this formation standing nearly on edge. Unless repeated of course this would represent approximately the thickness for Peekskill valley. But it is not believed to be so thick. It is more likely that there is a threefold occurrence brought about by close isoclinal folding (a closed s-fold) as seen in the accompanying cross section. This view is supported by at least one occurrence of the underlying quartzite member near the center of the valley at a point a couple of miles farther north On the line of exploration, however, none of the borings penetrate any other formation beneath. Attention is called to additional structural details and physical conditions in a later paragraph.

Quartzite. One boring (no. 5) is in a quartzite. It is very pure, fine grained, closely bound and typical quartzite. The beds stand almost vertical and the whole thickness is known from nearby outcrops to be approximately 600 feet. From its character and relations to other formations it is regarded as the Poughquag — a well known formation of the north side of the Highlands.

Gneisses. Five borings (no. 7 E, 9 B, 17, 27 and 28) are in gneisses. These are to a considerable extent simple granite gneisses of igneous origin. But there is the usual variety characteristic of the Highlands gneisses and no doubt they are representatives of the great basal gneiss series that is elsewhere referred to as the equivalent of the Fordham of New York city.

2 Stratigraphy

This is therefore the rock series of Peekskill creek. It is the only locality on the south side of the Highlands where all are represented in complete and simple form. There is no doubt that it is the Poughquag-Wappinger-Hudson River series, in spite of the complete absence of organic evidence. A similar though not so complete and clear occurrence is to be found on the west side of the Hudson near Stony Point and Tompkins Cove. That is a part of the same structural syncline. It is probable also that the phyllite so finely developed in the village of Peekskill in the next small valley to the east is the same. But outside of these occurrences there are none that clearly represent this same series as a whole and in the same condition.

No more striking example of this fact can be found than the adjacent Sprout brook described in an earlier section. There coarse crystalline and injected and impure limestone occurs alone — no phyllite and no quartzite. When one remembers that the two occurrences so strongly contrasted, Sprout brook and Peekskill creek, converge until they actually unite, and still preserve their stratigraphic dissimilarity, without any adequate structural reason for it, the only conclusion possible is that the two occurrences represent two entirely different series of formations.

The Peekskill valley series is Cambro–Ordovicic in age; what is the other? It is older, at least that is certain. But is it (the Sprout Brook limestone) as old as the oldest of the gneisses themselves and therefore interbedded with them representing locally the Grenville; or is it intermediate — Postgrenville and Precambric — with which possibly other occurrences of rocks of similar habit and equally uncertain relations belong?

It is on the general similarity of this occurrence to the Inwood limestone as known throughout Westchester county and New York city that a tentative intermediate series has been recognized. This is the Inwood-Manhattan series. Whether it is in reality a separate older series is not regarded as proven. But for engineering and practical purposes the distinction is a good one and eminently serviceable. Further discussion may better be continued in a different publication.

3 Rock surface

The bed rock surface is pretty well outlined by the borings. A profile based upon them seems to leave no unexplored space of sufficient extent to admit a gorge of great consequence to a lower level

than is already shown in holes no. 1 and no. 11 [*see* profile and cross section, fig. 33]. The elevation indicated by no. 3 D is believed to be misleading because of the use of a drill that was capable of destroying a part of the ledge rock that would usually core. The points believed to be weakened by structural disturbance and therefore most likely to be attended by erosion and stream action are in the vicinity of hole no. 11, near the present creek, and hole no. 25, near Peekskill Hollow road.

4 Buried channels

From the accompanying cross section it will be seen that the drift cover is more than 100 feet thick over large portions of Peekskill valley. The rock floor in the middle of the valley averages approximately 25 feet A.T., while the drift surface except where cut out by stream erosion is at about 125 feet. In the rock floor there are two depressions, the large one wholly within the limestone belt and the smaller following the limestone-phyllite contact. There is not much difference in their depth so far as explored, but there is a possibility of a somewhat deeper notch in each one. The depth to which some of the limestone beds are decayed by underground circulation would lead to the belief that a deeper notch may exist.

The drift cover is chiefly partially assorted sands and gravels in the central portion of the valley, and more of a till on the eastern valley side. It is noteworthy that the present Peekskill creek lies far to one side following closely the phyllite wall.

5 Underground water

Present elevation above sea level is so slight that there is apparently little encouragement of deep underground circulation. But at certain points the rock has been found to be very badly decayed to a great depth — to at least 200 feet below sea level. This is believed to have been accomplished chiefly at a time when the region stood at a higher level. Hole no. 22 is especially notable in this connection. A comparison of the figures of core saving is one of the best lines of evidence on this question. Wherever data are at hand the percentages of saving have been put on the cross section. Hole no. 29, for example, shows a saving of only 11% in the lower 250 feet, reaching a depth of 297 feet below sea level.

The present water table profile is shown on the cross section. A great body of water stands in the assorted sands directly upon bed

rock forming essentially a great reservoir of supply that has ready access to the almost vertical limestone beds. This will give a maximum water supply to holes that penetrate porous or broken portions of bed rock. The attitude of all strata is especially favorable for admitting an almost inexhaustible supply from a considerable drift-covered area within which circulation is probably very rapid.

6 Condition of rock

All strata of this valley stand so nearly on edge that drills actually explore a very limited portion of the whole series of beds. No very great advantage is gained by excessively deep boring because the drill follows necessarily almost the same bed from top to bottom. At best only the immediately adjacent beds are penetrated. This means that much of the total thickness of beds is untouched by present explorations, and must be interpreted on the basis of their general likeness to those more fully determined. The usual succession of beds is known to be quite uniform in quality and locations where they can be studied and there is no reason to expect greater variation here.

Deviations from such normal or uniform conditions are mostly due (*a*) to local development of mica from recrystallization of impurities in the limestone, and (*b*) to crush zones developed in the process of folding and faulting which has broken the rock or weakened it enough to permit a more ready circulation of underground water. Wherever either of these structural conditions prevail, the rock has been excessively decayed, or disintegrated, or sufficiently weakened in its binding matter or its sutures to crumble in the hand or break down to a sand under ordinary boring manipulation. This condition is known to reach to –297 feet. How much deeper is not known. Probably the decay dates back in large part to preglacial continental elevation at which time probably there was more ready deep circulation with possible outlet in the Hudson gorge. This action has been all the more effective by reason of the attitude of the beds. They stand so nearly on edge that they present all their weaknesses of bedding and sedimentation structures to the destructive surface agents. They admit surface water readily and favor abundant underground circulation.

Considerable faulting occurs. The contact between the granite-gneiss and quartzite is a fault contact. Wherever seen this is sound. But a crush zone in limestone lies nearly central in the valley, cut by holes no. 23 and no. 25, where the rock shows a finely brecciated

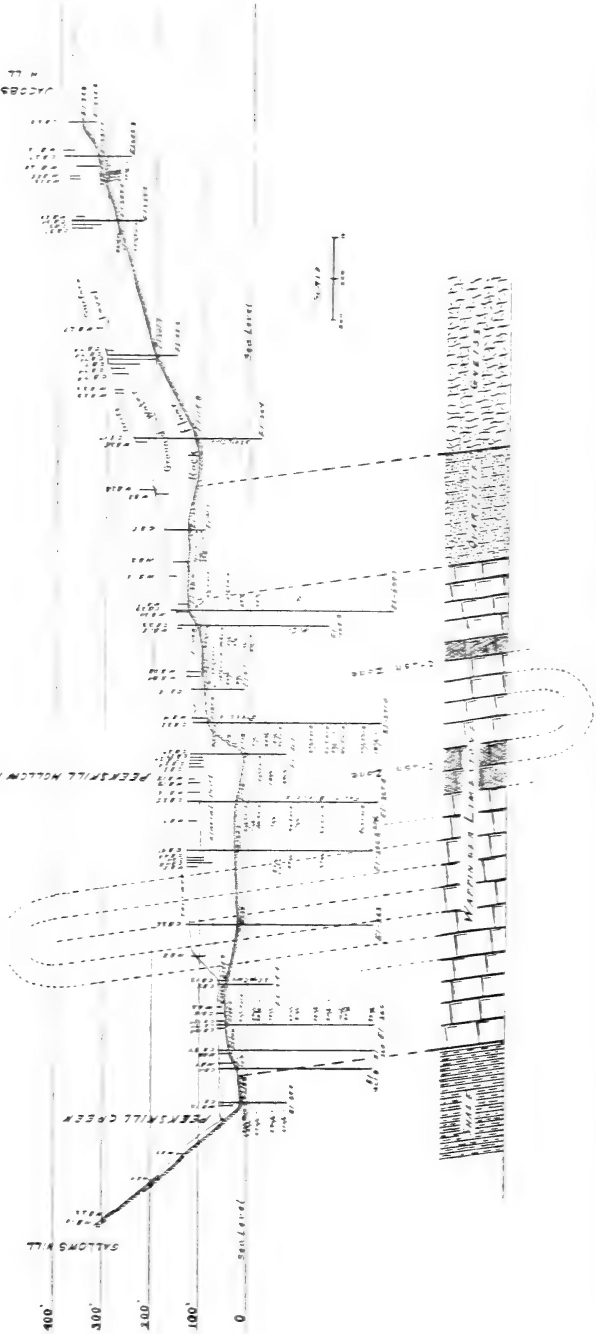


Fig. 33 Geologic cross section and detail of borings across Peekskill valley along the line of the Catskill aqueduct

condition some portions of the drill cores being literally crushed to bits.

In one hole, no. 11, near the phyllite-limestone contact, a soft, sandy condition was encountered at a depth of 133 feet, permitting the drill rods to be pushed down without boring at all, 60 feet ahead of the casing. This, however, is not believed to indicate any very extensive weakness. It is probably connected with the bedding planes or joints rather than with general decay or faulting. Four or five inches of solution and disintegration along bedding planes would account for all that has been proven. The fact that the rods could be shoved down 60 feet while the corresponding outer casing could be shoved down only half as far seems to support this view.

Summary

If a tunnel were made across this valley there would be approximately 1100 feet of it in Hudson River slate (phyllite), 3250 feet in Wappinger limestone, 600 feet in Poughquag quartzite, and the rest in the gneisses.

Some weak rock is certain to be found, especially in the vicinity of station 367+50 and 345+00 to 350+00. At both places increased water inflow would be encountered with almost exhaustless supply from the sands that lie on the rock floor above.

At about this stage in the exploration the Board of Water Supply decided to abandon the rock tunnel plan. The conditions found were considered by them too questionable. Steel pipe construction is to be substituted. As a result it is not likely that much more detail will be added to the structure of this very complex valley.

CHAPTER XII

CROTON LAKE CROSSING

It is proposed to finish Ashokan reservoir and the Northern aqueduct first. This so called Northern aqueduct reaches from the Catskills to Croton lake. Croton lake is the present supply of New York city and is already connected by two aqueducts with the city distribution. As a first step, therefore, and as an emergency measure the Catskill water will be delivered to the Croton system by finishing the Northern aqueduct first. As rapidly, however, as the whole project can be carried out the so called Southern aqueduct will be constructed to continue the Catskill water independently of the Croton supply to the city.

The Southern aqueduct department has charge of the line from Hunters brook on the north side of Croton lake to Hill View reservoir near the New York city boundary. During exploratory work it has been under the direction of Major Merritt H. Smith, department engineer, with headquarters at White Plains. Construction now going on is in charge of Mr F. E. Winsor, department engineer.

The first link in this southerly extension is to be a tunnel beneath Croton lake through which the Catskill water may pass in the same manner as it crosses other valleys. This crossing has been located a short distance below the old dam on the Croton, about 5 miles up stream from the Hudson.

The problems involved at this point include (1) a determination of the kinds and quality of rock to be penetrated, (2) their water-carrying capacity, and (3) opinion as to the proper depth for a successful tunnel.

Geological features

The Croton valley is one of the very few in southeastern New York that actually crosses the geological formations and major structural features instead of following parallel to them. In its lower portion it passes from gneiss to limestone and to schist several times. The reason for this somewhat abnormal course is probably the development of weak zones by fault movements in this transverse direction.

Only one of the well known formations of rock is exposed in the immediate vicinity of the tunnel site. This is the *Manhattan schist,* the uppermost formation of the region south of the Highlands. Along the Croton it varies greatly, the chief type being a

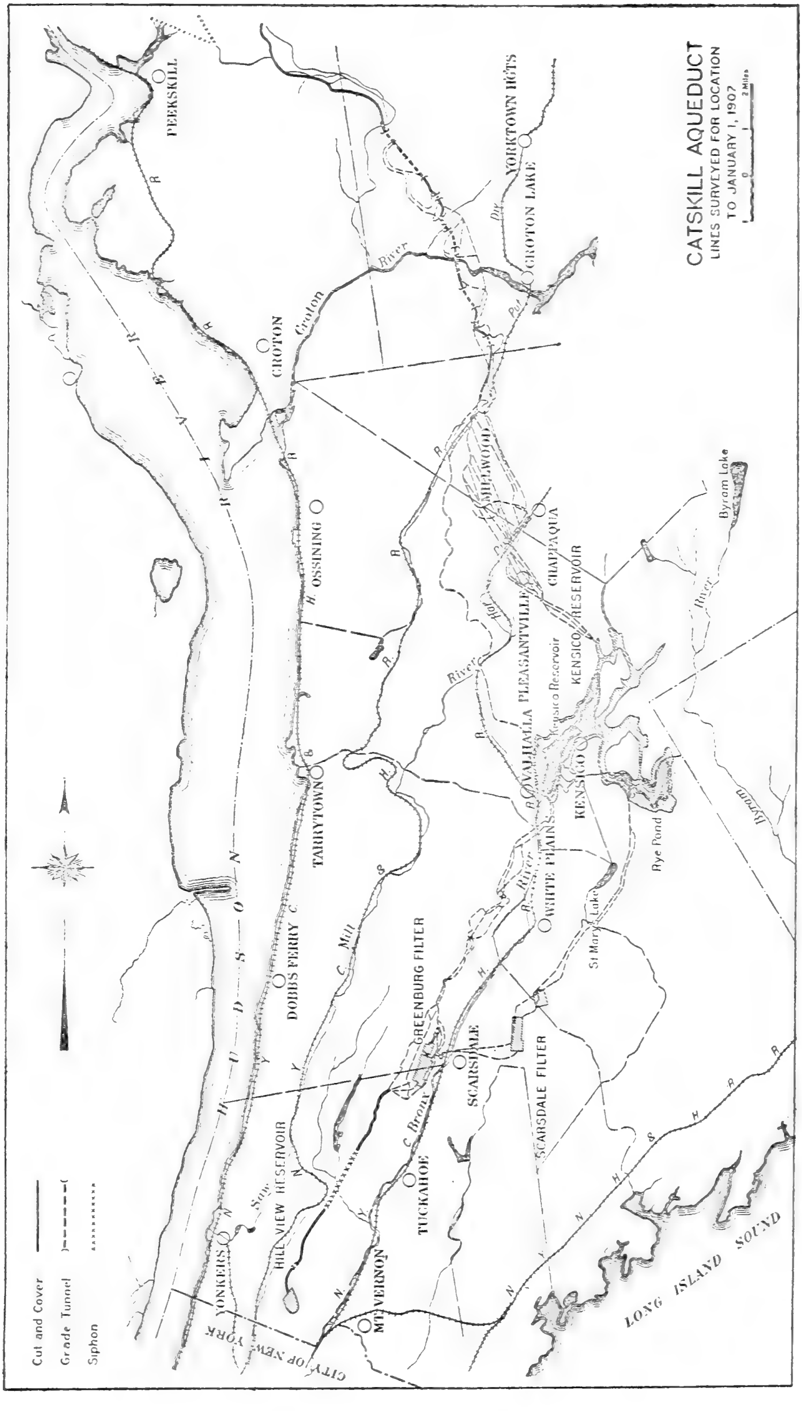


Fig. 34 General location map of the Southern aqueduct and associated parts of the Catskill supply

garnet-bearing quartz-mica schist varying from rather fine grain and semigranular appearance to a very coarse and strongly foliated structure. This part of the formation undoubtedly represents recrystallized or metamorphosed sediments. But associated with this facies there is a more dense black hornblende schist that, not only here but at many other places, is thought to represent igneous intrusions that have been metamorphosed together with sediments of various types, until both have lost almost all of their original characters. The hornblendic schist type is not so extensive as the other, the mica schist, but it is more compact and here as usual is in the better condition.

Pegmatite stringers occur abundantly, especially in the mica schist varieties. They are of no great consequence, however, as a factor in this study. They originated in the aqueo-igneous activity involved in the recrystallization of the rock when it was worked over into a schist.

Beneath this Manhattan schist formation lies the *Inwood limestone,* a bed probably at least 700 feet thick. But at this point how deep it lies and at what depth it would be penetrated nobody can tell. None of the drills have touched it. Beneath the limestone in turn lies the granitic and banded gneisses belonging to the *Fordham gneiss series,* the lowest and oldest of the region.

Along the Croton river nothing but Manhattan schist is to be seen at the surface for more than a mile above and below the proposed crossing. The same thing is true for an equal distance on opposite sides from the river at this locality.

But the structure is folded and the normal northeast-southwest trend of the folds crosses the river, every arch or anticline tending to bring the limestone and gneiss nearer to the surface. One of these folds does expose the limestone and gneiss in a strip extending from the Hudson river northeastward for two thirds of the distance to the old Croton dam. But before reaching the Croton valley this fold pitches down toward the northeast beneath the Manhattan schist and passes under the present lake (or reservoir) in that relation, not reaching the surface again for a distance of about 6 miles. At least one more fold is known to behave in a similar manner as it reaches the Croton.

These facts make it certain that there is limestone beneath the schist in the vicinity of the crossing, and that it comes nearer to the surface in that vicinity than at some other places.

South of the Croton there are several small cross faults run-

ning nearly east and west. It is believed that similar movements have affected the rock in the Croton valley itself, modifying its condition so much as to control the course of the stream. The only immediate bearing upon the problem of the Croton crossing is the question that it raises about the quality of rock and the necessity that is introduced of trying to determine whether or not there is shattering enough to be very objectionable.

Explorations and data

Six drill holes have been made on this proposed Croton lake crossing — one on either side just at the margin and four others within the intermediate space of 1400 feet. These inner four have been made from rafts floated on the lake and have penetrated water, drift cover, and rock [*see* accompanying profile and cross section, pl. 27].

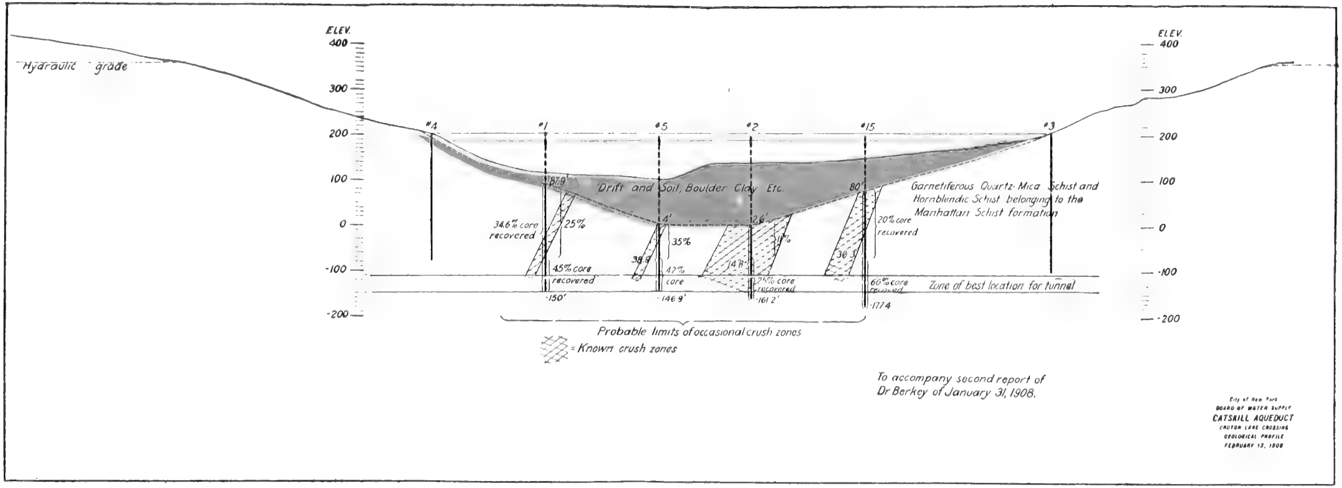
Rock floor. The depth of the preglacial Croton valley is pretty accurately determined at 0 feet or sea level. There is no reason to expect a gorge or inner channel of any consequence.

The drills have penetrated only one formation, i. e. Manhattan schist. These test holes are believed to be near enough together to eliminate the possibility of any other formation appearing at tunnel grade.

Rock condition. The two varieties of schist (1) the coarse garnetiferous quartz-mica rock, which is a metamorphosed former sediment, and (2) the darker, close grained hornblendic rock that is believed to represent an igneous intrusion, both occur in the cores brought up by the drill. Either under normal conditions is a good rock. But there are considerable differences in the physical condition of the rock. Holes no. 3 and no. 4 at the two extremes, on the lake borders, show sound rock that comes up in large cores with very high percentage recovery. This is confidently believed to represent the average condition of the rock in this vicinity at the sides of the valley.

The central holes, however, nos. 1, 2, 5 and 15, all show more broken ground. Of these holes no. 2 is much the most broken, the core recovery being only 14.8%. The pieces are small and many are smoothed (slickensided) by movement. The hole penetrates a typical crush zone resulting from slight faulting movements, and the low saving is due to the fact that the incipient fractures are not well bound together (rehealed) by later mineral change. They are probably connected with the latest movements of this kind.

Plate 27



Cross Section of the Croton Valley at the Crossing of the Catskill Aqueduct.

The tunnel is to pass beneath Croton lake, the present water supply of New York, and carry the Catskill water under pressure to the south side where it will rise to grade again. The rock is all Manhattan schist of both mica and hornblende varieties. The study covers chiefly depth of drift cover, position and extent of crushed rock, probable water circulation, and depth for suitable rock condition.

The commonest secondary mineral now filling these crevices is chlorite, and, although it may completely fill the crevices it has little binding strength. Any new disturbance or strain readily causes separation along the same original lines. But in spite of the fact that the core is broken into small pieces and shows so low percentage of recovery it is quite certain that the rock itself is not badly decayed. An examination of one of the most doubtful looking cores from the lower part of hole no. 1 showed under the microscope little evidence of serious decay. This is believed to mean that underground water circulation is not as abundant as the fractured condition of the rock would lead one to expect. Furthermore, an examination of the cores in greater detail shows beyond question that much of the fracturing is entirely fresh and must have been done by the drill itself. It is certain that the low percentage of recovery is in part due to this cause. The small diameter of the intermediate holes is contributory to the same results. Some allowance must also be made for the difficulty of working a machine from a raft on the lake.

Comparison of the cores shows a decidedly higher percentage of core recovery, and presumably therefore of rock solidity in all of the other three holes — no. 1, no. 5 and no. 15.

Hole	no. 2 —	core recovered	14.8%
"	no. 1 —	"	34.6%
"	no. 15 —	"	36.3%
"	no. 5 —	"	38.9%

It therefore appears that the last three penetrate rock that is more than twice as good in its capacity to stand drilling disturbance.

A comparison of quality at different depths is believed to be still more encouraging. The upper portions of all holes have poor recovery and comparatively poor looking rock. But in depth there is a marked improvement.

In view of the fact that the tunnel will undoubtedly be located somewhere below the –75-foot level, it is really only this lower section that is of vital importance to the project. A tabulation and comparison of core recovery from these lower portions is given below.

	1 From total depth of hole		2 From depth –75′ to bottom	
Hole no. 2 —	= 14.8%	core recovery	25%	core recovery
" no. 1 —	= 34.6%	"	45%	"
" no. 15 —	= 36.3%	"	66%	"
" no. 5 —	= 38.9%	"	42%	"

Under the conditions of work, this is a fair saving and indicates much more substantial rock below the −75′ level. There are many pieces 10–12 inches in length and for a 1 inch core this may be considered very good.

It is clear, however, from a detailed inspection of the cores, that there is considerable variation somewhat independent of depth. There are occasional stretches of poorer ground in the midst of comparatively sound rock. This is believed to indicate that the crushed condition is confined chiefly to certain zones, and that these zones dip across the formation and across the holes at an angle. They are probably distributed promiscuously throughout the central portion of the valley, but are certainly more abundant and more strongly marked in the vicinity of hole no. 2 than at any other point tested. The rock profile shows that hole no. 2 has also the lowest bed rock. This is a further support to the general explanation of the valley as given above.

The chief elements of uncertainty remaining after the borings have been completed are:

1 The exact extent or widths of the chief crush zones
2 Their dip and strike
3 The possibility of others not yet touched
4 The permeability of the rock for underground water
5 The supporting strength of such rock in a tunnel of large dimensions

In spite of the uncertainties enumerated, the conditions are entirely understandable. There is little probability of finding a worse condition than that shown in hole no. 2. The permeability or porosity of these zones is of course unknown. The chief reason for believing that underground circulation is not abnormally heavy is the observation that the joints are well filled with chlorite and that other decay is not at all prominent at the lower levels. Furthermore, the rock is a crystalline type of rather successful resistance to ordinary solution agencies and therefore may be depended upon to hold its own in its present condition indefinitely. But because of the poor binding effect of the chlorite it is to be expected that blocks will fall from the roof of any tunnel where it passes through a crush zone. Timbering will be required for protection in places, but the ground will not cave or run. These zones may be expected throughout a total distance of about 700 feet — i. e. the space between no. 1 and no. 15. The chief belt of such ground probably lies between holes no. 2 and no. 5.

Summary

The lowest bed rock is about sea level.

This pressure tunnel will cut only Manhattan schist.

All rock is good ground for such work, except in certain narrow zones where it is crushed.

The extent of such broken ground is not closely delimited, but occurs at intervals for a distance of 700 feet.

The amount of underground circulation is judged to be moderate at −100 feet.

The tunnel should be located deep enough to take advantage of the improved rock conditions shown at about −100 feet. There seems to be no marked improvement below −100 feet as deep as the drills have gone.

CHAPTER XIII

GEOLOGY OF THE KENSICO DAM SITE

Kensico reservoir at Valhalla, 2 miles north of White Plains, is one of the links in the Bronx river aqueduct. It is to be greatly enlarged and made a very important storage reservoir for the new Catskill system. In line with this plan a new dam is to be built near the old site that will rise 100 feet higher than the present structure.

Extensive investigations[1] have been made to determine the character of rock floor for this massive dam. Sites both above and below the present one have been studied with the question of safety and efficiency and permanence as well as that of economy of construction in view. Involved with this is also the source of suitable stone for its construction.

Geological surroundings

Glacial drift covers the rock floor of this and neighboring valleys to a depth of 10 to 20 feet. No rock is exposed in the valley bottom at the Kensico site, but at the extremities of the proposed dam the rock floor comes to the surface in small outcrops. The material constituting the drift cover is essentially a loose, somewhat porous till passing into modified types, especially gravels and sands immediately south of the ground tested.

The character of bed rock at the two extremities and beyond the limits of the dam is easily seen from the outcrops to be Fordham gneiss on the east and Manhattan schist on the west. Between, although nothing can be seen, Inwood limestone is found by the borings as was to be expected. No other formations occur, although the Yonkers gneiss, an intrusive in the Fordham at a little greater distance figures prominently in studies of material.

The formations are in normal order and are of the usual petrographic character. All dip westward at angles that vary from 45 to 65 degrees and have a general strike a little east of north. It is evident that the whole series represents an eroded limb of a simple fold.

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[1] These explorations have been in direct charge of Mr Wilson Fitch Smith, division engineer, whose headquarters for the Kensico division is at Valhalla, N. Y. Preparations for construction have already been begun.

The Inwood limestone occupies about 800 feet of the bottom and eastern margin of the valley, lapping well up on the Fordham gneiss. The drill cores from this formation are unusually sound.

The Manhattan schist shows much broken material. There are many crush zones. This condition increases still farther west along the railway near Valhalla station.

The Fordham gneiss appears to be sound where it can be seen at the surface.

Results of exploration. Many borings have been made. They prove the general structure and succession of formations, making the boundaries definite. They increase the evidences of a rather wide prevalence of weak zones — some of them in the gneisses. And they also indicate a more extensive surface decay than was formerly believed to prevail.

The chief problems from the geologic standpoint are connected with the following features:

1 Extent of surface disintegration

2 Extent and distribution of weak zones

3 Depth of decay and perviousness of rock

Surface disintegration. Several borings on ground underlain by Fordham gneiss penetrated material beneath the drift and above bed rock that was interpreted as residuary matter from rock decay. All of this material is of local origin. Later exploration in the form of a deep trench to bed rock has proven that there is an extensive residuary mantle of this sort at the eastern side of the valley below the present dam. In places as much as 30 feet exists. Undoubtedly this material is a remnant of preglacial soil mantle that was in some way protected from removal by the ice. Few places are to be seen in all southeastern New York where there is so much left in place. In most of it the gneissic structure is still preserved, but the decay is so complete that it can be cut and handled like an impure clay.

Weak zones. It has been proven that there are weak zones in the gneisses as well as in the other rock formations. In some places the rock is so poor that no core is recovered for distances of 5 to 10 feet, and in one hole a seam of this kind 20 feet wide appears. In every case, however, the drill passes through the rotten material into the opposite wall — indicating a zone of considerable dip instead of vertical position. This favors the theory that the weaknesses follow the bedding largely and are perhaps due to

difference in the mineral make-up of the beds fully as much as to dynamic disturbances. The walls are generally good. The fragments of core are not much slickensided. In the schist this is probably not as generally true. There are much plainer evidences of crushing movements in the schist. It is a locality where one of the folds, one well developed farther south, is pinched out and there is rather general crushing of the weaker strata.

Depth of decay and perviousness. As deep as borings have gone there is occasional decay and broken material and streaks that are pervious.

Final location. The condition of bed rock, together with other considerations led finally to the selection of a site above the present dam. In general the same features characterize this site. But the rock condition is somewhat improved. On the whole the new situation is a safer one.

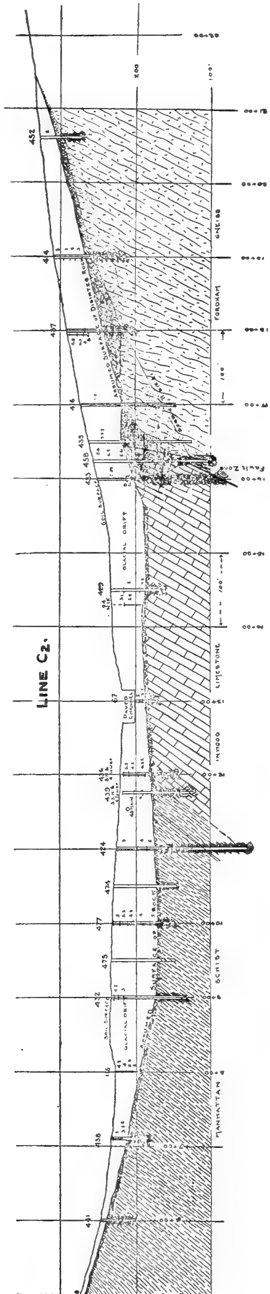


Fig. 35 Geologic cross section across Bronx valley at Vallhalla as indicated by borings on line C2 a short distance below the present Kensico dam

CHAPTER XIV

STONE OF THE KENSICO QUARRIES

The following quarries in the immediate vicinity of Kensico reservoir have been studied in the field:

(1) "Smith quarry," which is less than a thousand feet east of the southern end of the present reservoir; (2) "City quarry," which is on the immediate eastern margin of the reservoir on the east side; (3) "Garden quarry," which is a new location about 500 feet from the eastern margin about midway; (4) "Outlet quarry," 1500 feet east of the northern extremity of the present reservoir; (5) "Ferris quarries" 1000 feet and (6) "Dinnan quarry" 3000 feet farther north.

In addition to the field observations a detailed microscopic study was made on specimens of the rock taken from the Garden, Ferris and Dinnan quarries.

The question at issue is the choice of a rock for the facing and finish of the new Kensico dam. In view of the use to be made of the rock, extreme strength is of only secondary importance. But the questions of abundance, distribution, durability, purity, agreeable appearance and working quality are vital.

Types of rocks

All of the quarries occur in the broad belt of Precambric gneisses that forms the eastern margin of the reservoir extending northward and southward for many miles. The formation as a whole is very complex. But the basis of it is a black and white banded rock chiefly a metamorphosed sediment, known as the Fordham gneiss in southeastern New York. In it are intrusions of igneous rocks of many varieties and most complicated structure — dykes, bosses, veinlets, stringers etc., sometimes in such abundance as to wholly obscure the original type. The most abundant of these are, (*a*) a rather light colored quite acid rock that is essentially a granite in composition, but has a sufficiently foliate structure to be classed as a gneiss and is the same as the "Yonkers gneiss" occurring farther south, and (*b*) a dark rock containing much hornblende and biotite which is in some cases essentially a diorite in composition, but has a marked tendency to schistose structure. The former (*a*) may be called a granite gneiss and the more massive representatives of the latter (*b*) may be classed as a dioritic gneiss. In both cases at

times the blending with the original metamorphosed Fordham gneiss is so intimate that absolutely sharp limits can not be drawn. And this last condition may well be designated as a third case (*c*).

The quarries visited represent all three of these cases. Dinnan, Ferris and Outlet quarries represent essentially the "Yonkers gneiss" type (*a*) of granite gneiss. Garden quarry represents chiefly (*b*) the dioritic type of gneiss. City and Smith quarries represent the last case (*c*), or the mixed and variable type.

Field character

City quarry. In accord with the above differences in type it is found that large quantities of uniform material for such purpose as is proposed can not be obtained from City quarry. The rock there is badly jointed and is variable to a marked degree. It was not thought promising enough to test in detail.

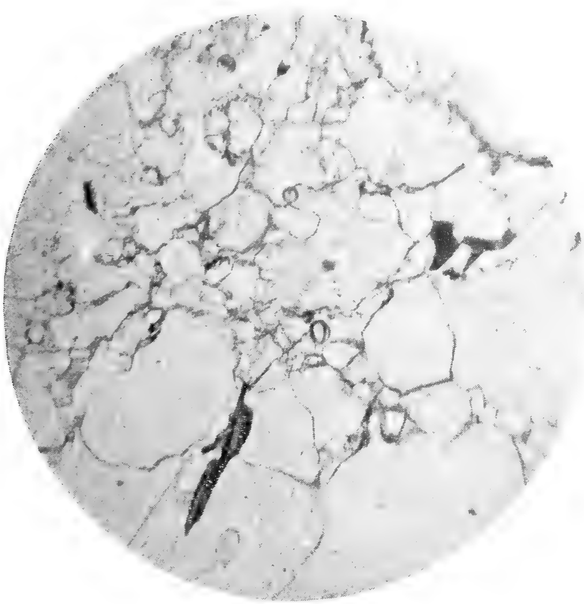
Smith quarry. The conditions of Smith quarry are better but there are similar objections. The amount of uniform material is greater. It would no doubt furnish an abundance of material suitable for use in the construction of the dam interior, but is not at this point as good a source of facing stone as some of the others to be considered.

Outlet quarry. Although this rock is characteristic Yonkers gneiss, it has at this place suffered by weathering a peculiar discoloration to such extent as to make it objectionable, both from the standpoint of appearance and perhaps of durability.

Garden quarry. There is an abundance of stone at the Garden quarry. It is fairly uniform. It is no doubt good enough from every standpoint of durability. It is well located. It can be quarried readily. But it has a very dark color and is undoubtedly less attractive than a light stone for this purpose. There are no objectionable structures, except where the strong schistose character is developed, and these could be avoided so that with a little selection a fairly uniform stone could be secured.

Dinnan quarry. This rock is typical "Yonkers gneiss." There is sufficiently large quantity. It is of good quality. It is situated a little over 2 miles from the proposed dam, but is of easy access. The jointing and other structures do not seem to be objectionable. It will work somewhat more easily than a true granite because of the gneissic structure and it has a good medium light color. The discolorations do not seem to penetrate deep and the rock shows only slight decay.

Plate 28



Photomicrograph of Yonkers gneiss from "Outlet quarry" taken in plain light to show prominence of sutures between the grains indicating the beginning stage of disintegration. Magnified about 30 diameters

Ferris quarries. The "Old Ferris quarry—is "Yonkers gneiss" considerably more weathered than the Dinnan. It is considered less promising than the "New Ferries" quarry which has been explored by the engineers of the Kensico division. The rock of this quarry site is not all of one quality. There are essentially three varietal facies of the Yonkers gneiss type and relationship. One (*a*) is essentially a granite. It has a coarse grain and shows almost no foliate structure. It has a decidedly massive appearance; but it is not of very great extent. This rock is evidently very closely related to the true Yonkers gneiss into which it passes on all sides through an intermediate variety.

This intermediate variety (*b*) has medium size of grain, is only slightly foliated and passes without sharp limitations on the one side into the granite facies and on the other to true normal Yonkers gneiss. It is not so strikingly massive as the granite, but is more so than the gneiss proper. This rock may be called a gneissoid granite to distinguish it from the other.

The true Yonkers (*c*) gneiss surrounds these two special varieties. It is of finer grain than either of the others and is more strongly foliate and is strictly a granite gneiss. Varieties (*a*) and (*b*) occur as sort of a lens within the Yonkers gneiss.

The extent of the granite as now uncovered at the site is believed to represent its limits. The prospect of enlarging the area will not meet with much success. It is essentially a local development connected with the differentiation of the parent magma from which all three varieties were derived. It seems to have been the last of the three to solidify, and it has some of the characteristics of certain pegmatite lenses.

Although this is certainly an attractive rock and one against which there is little ground for objection, it is reasonably certain that a sufficient quantity of this variety can not be obtained here for the whole proposed use. And the prospects are not good for locating another quarry of the same quality.

The gneissoid granite (*b*) is of greater extent, in fact it will be found to encroach on the present area of the granite. It is as good rock and almost as attractive as the granite.

The regular type of Yonkers gneiss such as that represented in the Dinnan quarry can be obtained in almost unlimited quantity, and, with the splendid showing that it makes in further examination, it has come to be considered the best suited to the purposes of dam construction at Kensico.

Petrographic character of the rocks

This line of investigation is confined to four sets of samples.

No. 1 The granite of the New Ferris quarry
" 2 The gneissoid granite of the same quarry
" 3 The Yonkers gneiss of Dinnan quarry
" 4 The dioritic gneiss of Garden quarry

1 **Granite.** The rock is coarse grained and well interlocked. The chief constituents are orthoclase, quartz and microcline. There are but small amounts of dark minerals, and there is not much decay.

Both surface material and the drill core were examined. The deeper material shows a little calcite, that may be original, occurring in irregular grains. They do not seem to indicate decay. There is a little kaolin alteration of the feldspars, but not to a serious degree. There are no injurious impurities in the rock such as might cause rapid disintegration or discoloration.

The rock is undoubtedly of good grade as to strength, composition and durability.

2 **Gneissoid granite** (Ferris quarry). The rock is of medium grain, containing quartz, the feldspars and a little mica.

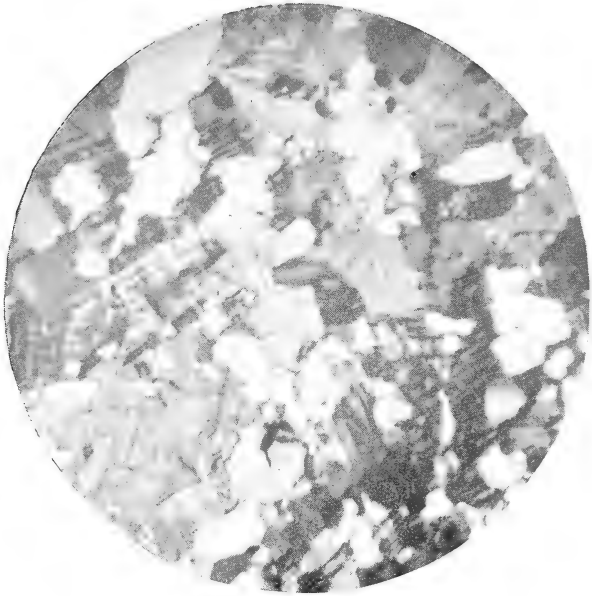
There is very little alteration, and no serious decay or injurious constituents. A small amount of sericite and calcite present are not considered of consequence, and as in the case of the granite, the calcite is believed to be original.

The grains are intimately interlocked and the rock is certainly of good quality and very similar to the granite proper.

3 **Yonkers gneiss** (Dinnan quarry). This rock is fine grained, and is composed of quartz, mica and the feldspars among which microcline is very abundant.

The condition is good,— very little alteration, close structure, but with a little more granular appearance than any of the other types. It is a good rock and gives good durability tests.

On badly weathered surfaces the Yonkers gneiss breaks up into a granular product like sand long before it decays to earthy matter. This seems to be caused by expansion and contraction of the different constituents under changing weather conditions inducing a weakening of the sutures. Sometimes there is very little decay even along these sutures, but as they open slightly they become the channels for moisture and staining solutions. This makes the boundaries of the grains very well marked in weathered specimens.



Photomicrograph of Yonkers gneiss of the type to be used in the new Kensico dam. Dinnan quarries. Magnified 30 diameters

Photomicrograph of diorite gneiss from "Garden quarry." Magnification 30 diameters. The constituents are hornblende, biotite, feldspars and quartz.

Such incipient disintegration is common in the more even grained or granular varieties.

The accompanying photomicrograph [pl. 28] is taken in plain light and shows the outlines of the grains due to this cause.

4 **Dioritic gneiss** (Garden quarry). Rock is of medium grain and with a strong tendency to schistose or foliate structure. The dark grains are hornblende and biotite, the light grains are feldspars and quartz.

The rock is fresh, durable and has no injurious constituents. It is good enough for the use in all respects, but has a dark color and is more strongly foliated than any of the others considered.

It is evident from these observations that the rocks considered are all of suitable mineralogic character for the purposes of large dam construction. For very large quantities of material, however, it is probable that neither the coarse granite nor the gneissoid granite could be depended upon for uniform supply. The true regular Yonkers gneiss, however, is very abundant, and can be relied upon for indefinite amounts. The dioritic gneiss is also abundant. The immediate region is not capable of furnishing any better rock than those described above.

Additional tests

Some instructive tests were made by the Board of Water Supply under the direction of Mr J. L. Davis who has charge of the testing laboratories. A few of these applying to the rocks at Kensico are tabulated below.

The tests cover: specific gravity, weight per cubic foot, porosity in per cent, ratio of absorption, per cent water absorbed, ratio of drying 24 and 48 hours, retained water pounds per cubic foot 24 and 48 hours.

In the accompanying tabulation the terms used are subject to the following limitations as to definition:

1 Ratio of absorption, sometimes called porosity, "is the ratio of the weight of water absorbed to the dry weight of the stone."

2 Porosity gives "the actual percentage of the stone which is pore space." "The difference between the dry and saturated weights of the sample is multiplied by the specific gravity of the rock and the product added to the dry weight. This gives the weight the specimen would have provided it contained no pore spaces. The difference between the dry and saturated weights

multiplied by the specific gravity of the rock is then divided by the above computed weight of the poreless specimen. This ratio expressed as a percentage is the actual porosity. Expressed as a formula, the computation is as follows:

$$\frac{(\text{Saturated wt.} - \text{Dry wt.})\ \text{S. G.}}{(\text{Saturated wt.} - \text{Dry wt.})\ \text{S. G.} + \text{Dry weight}} = \text{Porosity.''}$$

3 Ratio of drying. An attempt has been made to determine the comparative and actual rates at which the saturated rocks give up the absorbed water under ordinary atmospheric conditions. "The ratio of drying was computed by dividing the weight of water lost during exposure by total weight absorbed. The weight of retained water was computed." The comparison is most useful in rocks of like petrographic general character.

The other terms need no explanation.

TABULATION OF TESTS

Name	No. of specimen	Ratio of absorption per cent	Porosity per cent	Specific gravity	Weight per cubic foot	Per cent water absorbed	Ratio of drying		Retained water pounds per cubic feet	
							24 hours	48 hours	24 hours	48 hours
Granite, Ferris quarry, core No. 461	1	0.34	0.77	2.66	164.7	0.26	49.45	52.8	.224	.210
	2	0.31	0.84	2.65	164.0					
Gneissoid granite, Ferris quarry, core No. 468	1	0.32	0.81	2.63	161.0	0.28	67.48	69.88	.146	.145
	2	0.25	0.71	2.65	162.8					
Yonkers gneiss,	1	0.30	0.87	2.64	163.3	0.30	88.16	88.16	.057	.057
Dinnan quarry	2	0.39	1.01	2.64	161.0					
Dioritic gneiss, Garden quarry, core No. 459	1	0.42	0.68	2.83	175.4	0.21	62.5	62.5	.137	.137
	2	0.24	0.68	2.86	174.8					
Gneissoid granite, Ferris quarry, surface	1	0.37	0.96	2.63	162.5	1.08	86.7	88.2	.252	.215
	2	0.98	2.50	2.62	159.4					
Granite, Ferris	1	0.44	1.12	2.63	162.3	0.40	70.0	74.0	.207	.180
quarry, surface	2	0.19	0.50	2.71	167.3					

Mr Davis concludes from a careful analysis and interpretation of these tests that the Yonkers gneiss is of superior durability.

CHAPTER XV

THE BRYN MAWR SIPHON

Geologic conditions as shown by exploration for a proposed pressure tunnel

Bryn Mawr is a railway station 2 miles northeast of Yonkers. The general features of the vicinity, its topography, succession of formations and the boundaries are shown on the accompanying sketch map which is largely copied from United States Geological Survey Folio No. 83. The Southern aqueduct follows southward along a Manhattan schist ridge until, at a point about a mile northeast of Bryn Mawr, a cross depression of so great width and depth is reached that some special means of crossing has to be devised. Near Bryn Mawr station a gneiss ridge rises and continues southward. The proposed line follows this ridge.

Explorations have been made as usual by drilling to determine if possible whether or not a bed rock pressure tunnel is practicable.

The following questions may be made to cover most of the practical issues of the study:

1 What formations would the tunnel cut?

2 Which of these would show most questionable ground?

3 What portion of the line is regarded as most critical — whose development would show whether or not a tunnel is practicable?

4 What special conditions are shown by drill borings?

5 What interpretation is to be placed on the peculiar results from hole no. 4 where there has been unusually great difficulty in drilling?

6 What experiences in similar ground have a direct bearing on this case?

Formations

The formations that would be encountered in the Bryn Mawr siphon are:

1 Manhattan schist (top), the usual micaceous type, also called Hudson schist in United States Geological Survey Folio 83.

2 Inwood limestone (middle), the usual coarsely crystalline dolomitic and micaceous type, also called "Stockbridge dolomite" in the Folio, same as "Tuckahoe marble," same as "Sing Sing marble," same as limestone at Kensico dam and also at Croton dam.

3 Fordham gneiss (bottom), the usual black and white thinly banded type, a much folded and strongly metamorphosed rock, the oldest of all.

4 Yonkers gneiss, the usual type, gneissoid biotite granite very uniform and granular. This formation is an igneous intrusive that cuts up through the Fordham gneiss and is therefore younger. Whether it is also younger than the limestone and schist is not clear.

5 Quartz veins and lenslike segregations of quartz, also pegmatitic streaks, are occasional occurrences in all of the formations. They are most abundant in the schist, but are seen also in the Fordham gneiss. A similar development was encountered in the limestone in hole no. 40.

6 Glacial drift, chiefly modified drift, partially stratified sand and gravel, reaching more than 125 feet in depth, covers portions of all formations.

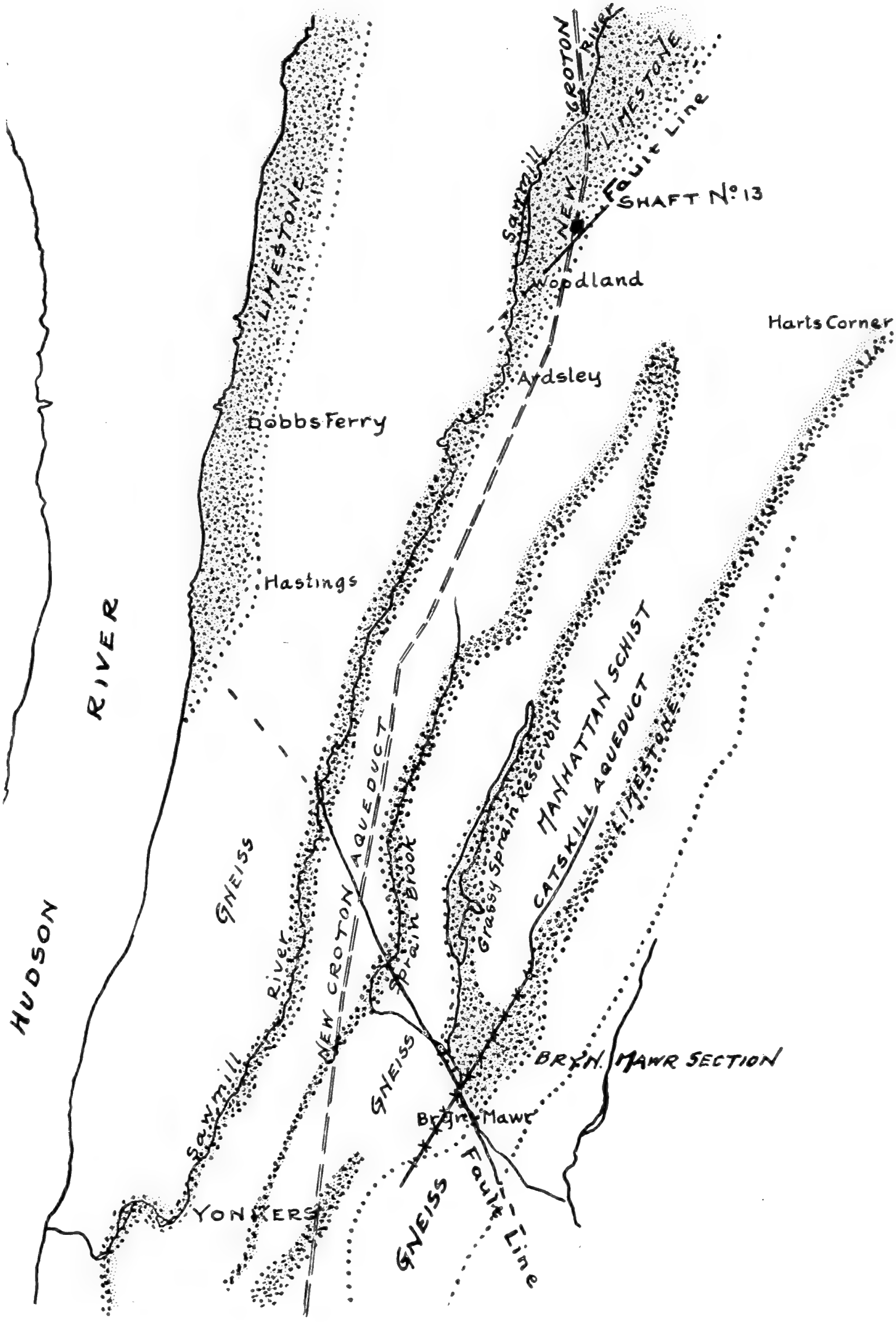
This last formation (no. 6) is the only one that may be wholly avoided in the tunnel proper. The chief interest lies in its hindrance to exploration and its possible usefulness as a source of sand and gravel supply.

Weakest formation. The Inwood limestone is the most questionable ground. This is believed to be so chiefly because of the greater solubility of the rock, its granular and micaceous character, and the probability that a line of displacement accompanied by some fracturing crosses the siphon line in this formation. If a very excessive amount of shattering occurs in this zone it may have induced a condition of disintegration to such depth as to endanger the tunnel.

There are no surface indications of a serious condition at depth for any of the other formations.

Critical zone

The critical zone is probably not far from the contact between gneiss and limestone. There are two reasons for this opinion. The first is related to the nature of the folding. The formations are squeezed into a close syncline pitching northward. In cross section the strata at any point around the head of this trough dip inward, and, because of the more resistant Fordham gneiss forming the floor of the trough, the drainage and seepage and consequent tendency to decay might be expected to follow along its upper contact.



Location map showing by the dotted belts the distribution of Inwood limestone in the Hastings-Yonkers district and the position of the Bryn Mawr tunnel section as well as shaft 13 on the New Croton aqueduct with their relations to the limestone belts. Manhattan schist and Fordham gneiss occupy the rest of the area.

The second reason is related to the probable later faulting movements. It is evident from the map [Folio 83] that the formations in the vicinity of Bryn Mawr are bulged up. One would expect the trough which contains the schist and limestone of Grassy Sprain valley to continue uninterruptedly southwestward and join with Tibbit brook valley. But a cross fold has bulged the formations up so much that for a distance of a mile erosion has removed all of the formations except the gneiss. Bryn Mawr station is about central on this bulge. Evidence of such a movement is readily seen on the gneiss along the northerly margin where it slopes down toward the limestone. The movement had developed a little shearing and has tilted the minor folds downward toward the north at angles varying from 30° to 80° from the horizontal. This angle becomes somewhat more accentuated as the limestone is approached, and it is believed that it may pass a short distance into the limestone border. There is, however, no great amount of crushing evident in the gneiss and this may hold also in the limestone.

The fact that Sprain brook crosses the formations along this northerly margin and flows for 2 miles in a southeasterly direction may indicate a still later movement, probably faulting. There is no surface evidence of it except the abnormal course of the creek. But, if there is such a fault, it also crosses the siphon line in the same zone, i. e. in the vicinity of the limestone-gneiss contact, not far from the location of the present course of the brook.

Therefore it seems reasonable to conclude that the critical zone is near the contact, probably on the limestone side, and in the vicinity of the present course of Sprain brook. It is also probably cut deepest here by erosion. If this zone is in good enough condition to stand tunneling the rest of the line ought to be.

Conditions indicated by borings

All rock formations stand very steep. They vary from 80° to 90°. This means that very few beds can be explored by one hole, and that any weakness or crevice is likely to make a showing in excess of its true proportions.

The cores show considerable crushing. Some of the fractures are not healed, although weathering from circulation is not present on all of them. The micaceous layers are most affected by circulation. Some beds of this variety are considerably weakened even at depths of over 200 feet. Occasional seams have been encountered that give no core at all for several (even 20 or 30) feet. But the

greater proportion of the recovered pieces are comparatively solid even where the total percentage of saving is very low. It is evident that some of the core, a considerable percentage, has been ground to pieces in the process of boring. This is especially noticeable at hole no. 40.

Hole no. 40. Much trouble has been met in this hole. A careful analysis of the record and core and the behavior of the drill is interpreted as follows:

1 Partially assorted drift, chiefly sand and gravel was penetrated for 125 feet.

2 Limestone bed rock of fairly sound quality was struck at about 125 feet (about el. –40).

3 The casing that was put down to shut out the sand failed to reach solid rock, and this permitted a continual supply of pebbles and sand to run into the hole and obstruct the work with each pull up. The presence of these pebbles was also instrumental in grinding the core to pieces, and this accounts chiefly for the low saving.

4 After this opening was plugged up with cement, the drilling was continued successfully until a somewhat broken quartz vein was encountered and this has been followed for about 35 feet. Its broken condition afforded another opportunity for fragments to fall into the hole, and on top of the drill, bringing the work for a second time to a standstill. It is certain also that the drift pebbles still fall in. As the formation stands vertical here it is not surprising that any feature should show an apparent extent quite out of proportion to the real value. The quartz vein is probably of no great breadth. Small seams containing mud may also be followed 15 or 20 feet and still be of no great significance in the formation as a whole. The rock fragments (core) recovered in this hole are fairly sound.

5 In spite of the many delays and difficulties of this hole, it is apparent that the general rock formation is not responsible for it all. The failure to reach solid rock contact with the casing has been the cause of part of it. Later the penetration of a rather rare quartz vein, a thing that would not often be found in the limestone, has added to the trouble. Both of these causes are so rare that they may almost be given the value of accidents.

But the last 100 feet or more of the hole, from depth 225 feet to 335 feet, shows an unusually questionable condition. Only a few rock fragments are saved and they include limestone and quartz vein matter. The rest is wholly disintegration sand of rather complex composition but carrying very much mica. This is all wash

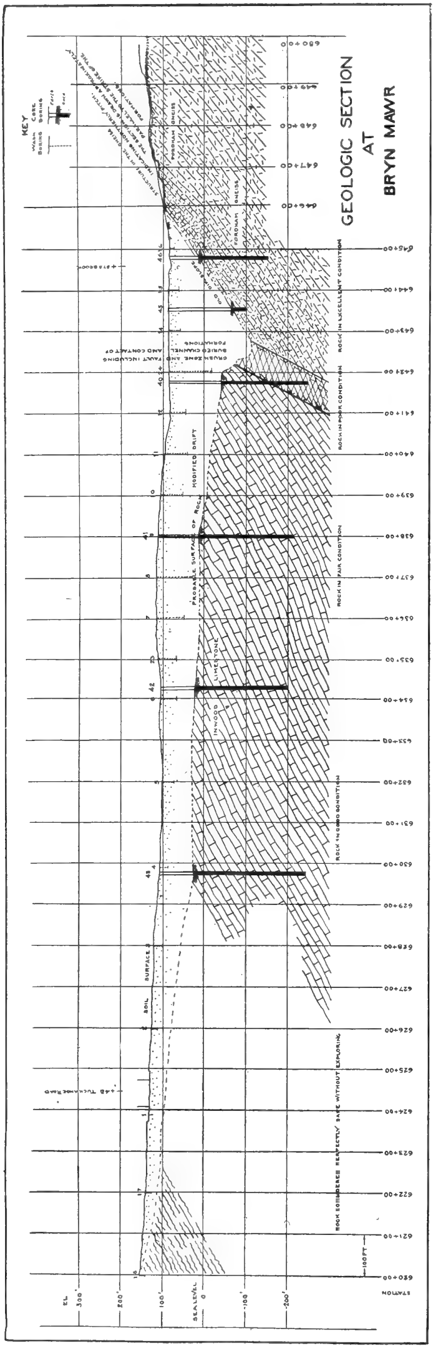


Fig. 36. Section along the aqueduct line from north to south showing the geologic structure interpreted from drill borings

material except one sample, which is a "dry sample" and is still more strongly micaceous.

Borings nos. 40, 45 and 46 are all within the zone that was considered, from surface indications, to be likely to carry the deepest gorge and to show the weakest rock. Because of the heavy drift cover (more than a hundred feet) it is manifestly impossible to locate the weakest zone more closely or judge of its exact condition except by borings.

Hole no. 42 at station 634 + 28, penetrates 82.4 feet of drift and reaches bed rock at about elevation 21 feet A. T. The rock is good, substantial, coarsely crystalline limestone. It shows as sound condition as can be expected in this formation even under the most favorable situations.

Hole no. 46 at station 644 + 77.4 is just south of the brook. It penetrates 72 feet of drift and reaches bed rock at elevation 14 feet A.T. The rock is Fordham gneiss of typical sort and in perfectly good condition. There is no question about the soundness of the rock from this point southward.

Hole no. 45 at station 643 + 52.5, 125 feet north of hole no. 46 penetrates drift for about 150 feet (possibly a few feet less, 145 feet). This drift cover is interpreted as mostly sand (modified drift) to 115 feet and a boulder bed from 115 to 143 feet. After the true ledge is reached it is sound and shows no unusual or questionable conditions. It is Fordham gneiss.

Interpretation

1 **Weak zone.** There is little doubt that this last 100 feet of hole no. 40 is in the decayed weak zone that was expected to develop in the vicinity of the contact between the gneiss and the limestone. It would be expected to pitch northward along the floor of gneiss and extend beneath the southerly extremity of limestone at this point [*see* fig. 36].

2 **Contact.** Hole no. 40 cuts limestone, hole no. 45 cuts only gneiss, therefore the formational contact lies somewhere in this 177-foot space.

3 **Position of old channel.** Bed rock surface is lowest at hole no. 45. But since the rock itself is sound gneiss, it is not believed to represent the lowest possible point. This is still more certain because of the fact that the pitch is northward so that this becomes a dip slope on which the preglacial stream could glide against the edges of the limestone beds [*see* diagram], and because the condi-

tion of the rock a little farther north (at hole no. 40) shows that these limestone beds are actually much weaker than the gneiss. Therefore the deepest portion of the buried channel is to be expected between holes no. 40 and no. 45, and probably nearest to hole no. 40.

4 **Depth of old channel.** How deep the buried channel may be can not be accurately estimated. But if the same dip slope as is shown by the rock surface from hole no. 46 to no. 45 prevails northward toward hole no. 40, a depth somewhat below –100 feet may reasonably be expected. In the absence of data bearing upon the depth of other portions of this ancient channel or of the lower Bronx river with which it must have been connected, it is impossible to estimate more closely.

5 **Interpretation of hole no. 40.** There is so little rock actually saved from the more than 200 feet of possible core on this hole that its real character is very obscure.

There are three possible explanations for the condition found in the last 100 feet.

a The drill may have followed a large mud seam.

b The material may be only residuary rotten limestone still wholly above the gneiss.

c The actual contact may have been penetrated and a part of this rotten material may be decayed gneiss within a crush zone.

The difficulty in drawing absolute conclusions is increased by the fact that matter falling in from above has been a continued source of trouble and is more or less mixed with the rock material of lower points. Therefore, the fact that the sand taken from the lowest points, 335 feet, is silicious instead of calcareous, may not prove satisfactorily that the rock at that point is wholly silicious.

It is worth noting, however, that the harder rock in the upper portion of the hole was in places much crushed and that mud seams were encountered before reaching this last 100 feet.

It is also worth noting that the same dip slope of rock surface as prevails between holes no. 46 and no. 45 if continued northward to hole no. 40, would cut that hole a considerable distance (75 feet) above its bottom.

In view of all the conditions, therefore, it is judged that there is a crush zone here, that hole no. 40 penetrates it, that it is badly decayed, that the plane of the crush zone dips steeply northward and cuts both limestone and gneiss, that a tunnel at about –300 feet would cut this zone south of station 640 and north of station 642, and that all other portions of the line are in comparatively satisfac-

tory condition. This zone for a hundred feet is likely to be wet, weak, and would require extra precautions and additional expense in construction.

6 Evidence of faulting. Whichever interpretation of hole no. 40 is taken is in support of some displacement in the nature of faulting between holes no. 40 and no. 45. If the gneiss rock floor is not reached in hole no. 40, then the greater northward slope of it from hole no. 45 to no. 40 than is shown from no. 46 to no. 45 indicates a downward movement. If on the other hand, the identity of the formation in the lower part of hole no. 40 be considered undetermined, and its condition attributed to decay in a crush zone, the presence of the crush zone itself indicates movement of a fault nature.

Conclusions as to character of the crossing

In considering the geological conditions as a factor in the problem of practicability of a tunnel, it is necessary to note the following points:

1 In view of the fact that the deepest point in the ancient channel is not yet found, and that it will probably go below –100 feet, it would be necessary to figure on a tunnel grade down well toward –300 feet.

2 It would be necessary to figure on a wet and weak zone of at least 100 feet along the tunnel and a more expensive construction at that point.

3 The ground at such depth south of station 642 is unusually sound. The ground north of station 636 may be counted good. The ground between 636 and 640 may be considered fair, and the ground from 640 to 642+, troublesome, containing the chief elements of uncertainty.

Fig. 36, which is a geologic section along the line at this point, shows the distribution of these features drawn to scale.

CHAPTER XVI

A STUDY OF SHAFT 13 AND VICINITY ON THE NEW CROTON AQUEDUCT

[*See* outline location map, pl. 30]

There has been reference made occasionally in connection with the Bryn Mawr explorations, as well as others, to the remarkable piece of bad ground encountered in 1885 on the New Croton aqueduct near Woodlawn in the Saw Mill valley. This experience has been the source of much misgiving. Because of its evident importance and close relationship to conditions that may exist in the same formation at points on the Catskill line, an examination of this ground was made for the purpose of comparison. The meaning of that case and its bearing on the Bryn Mawr questions are given below:

Engineer's records

This ground and its remarkable behavior is described by Mr J. P. Carson in the Transactions of the American Institute of Mining Engineers, September 1890, pages 705–16 and 732–52.

A description is also given in Wegman's *Water Supply of the City of New York,* 1658 to 1895, on page 152.

From Mr Wegman's report is taken the following:

The south heading was started from this shaft on June 1, 1885. It advanced at the rate of about 80 feet per month for 392 feet through good limestone rock (dolomite), which then became softer. On December 9, 1885, when the heading had reached a point 407 feet from the shaft a fissure was encountered from which about 100 cubic yards of decomposed limestone clay, sand and dirty water poured into the tunnel, partly filling it for a distance of 125 feet. After three days delay, when only clear water was flowing into the tunnel, the fissure was plugged with straw. The heading was advanced 20 feet further until on December 22, 1885, an outpour three times greater than the first occurred, covering everything in the heading out of sight * * * borings were made on the surface with a diamond drill to determine the extent of the soft ground in front of the tunnel. It was found to lie in a pocket in the rock,

which had a length of 110 feet on the axis of the tunnel and extended for a short distance below the invert of the conduit. The soft material, consisting of sand, gravel, clay and decomposed rock had a depth of about 160 feet from the surface to the top of the tunnel. It exerted such a pressure against the timber bulkhead that the 24-inch oak logs used as " rakers " (braces) became crushed in 24 hours and had to be continually renewed.

The chief points of present interest are that the tunnel, at a depth of about 160 feet from the surface, and after passing through several hundred feet (407 feet) of good dolomite, came into rotten rock and soft ground 110 feet across on the line. It was so soft that it ran into the tunnel in great quantities and exerted such pressure as to make progress in it a very troublesome and costly matter, taking " 60 weeks to advance the tunnel 85 feet " and costing " $539 per foot." The material caved in so freely as to form a pit on the surface.

Statement of geologic conditions

It is not possible to interpret the conditions at this locality as fully as one would wish because of the vagueness of some of the statements, but the following facts and explanation are essentially correct:

1 The rock is the Inwood limestone, the same kind and same general conditions as all of the limestone belts that occur in the region of the Southern aqueduct.

2 The soft ground penetrated at the point in question — 407 feet south of shaft 13 — called in the Carson report and others " a fissure " or " pocket," etc., is in reality a fault crush zone. The fault plane probably dips steeply southeast and strikes n. 50° e. cutting the tunnel line at an angle of something like 20°.

3 The point is well up on the side of the valley more than a hundred feet above Saw Mill river, and the strike of the fault zone in its southwesterly extension cuts into the lower portion of the valley, so that underground circulation would be encouraged along the zone in this direction.

4 The limestone outcrops very near by on the west side of the line and the Manhattan schist occurs near by on the east. The attitude of the beds is such as to indicate a fault of the thrust type, The accompanying figure illustrates this relationship in a cross section at right angles to the axis of the tunnel [*see* fig. 37].

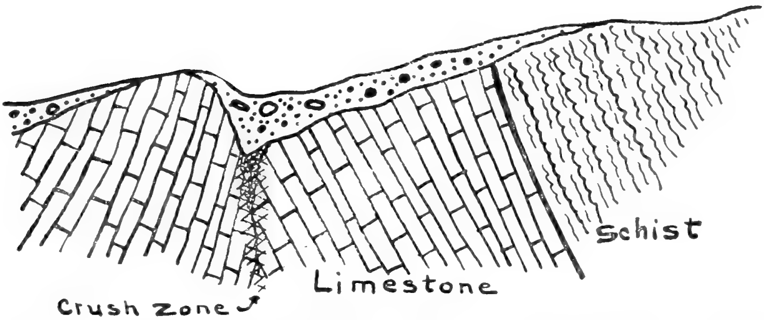


Fig. 37 Sketch of the geologic structure at shaft 13 on the New Croton aqueduct. Interpreted from field observations

5 It would appear probable that this zone was penetrated at the worst possible level, i. e. near enough to its wholly decayed upper part to furnish no resistance at all to the overlying sand and gravel, and not deep enough to reach the more substantial (although probably crushed) rock that may reasonably be expected to prevail at no very much greater depth.

The chief point is that the weak spot has a reason and is not an accidental thing that might be expected just anywhere. But it must be admitted, in spite of this fact, that a casual examination of the locality would not make one suspicious of its existence, and it is surprising that the spot could have caused so much trouble.

From the above it will be seen that in several respects the Bryn Mawr case is somewhat similar to this. They both indicate faulting; they are in the same type of rock; they both show or indicate caving tendencies.

On the other hand, there are certain elements of difference some of which are capable of very materially modifying any conclusion that might be based upon the simple facts of likeness. For example — it should be expected (1) that the fault movement at shaft 13 would be the greater because of lying in the more prominent lines of such displacement of the region, (2) being a thrust movement, the crush effect is probably more prominent at shaft 13 than at Bryn Mawr, (3) occurring at greater elevation above probable circulation outlet, the opportunity at shaft 13 for extensive and rather deep decay is the greater, (4) being cut so near the surface (160 feet), its condition there is not necessarily a reliable guide to the seriousness of decay at a greater depth.

Comparison of Bryn Mawr and shaft 13

The following statements embody an opinion on the points raised or suggested in connection with a reference to the New Croton difficulties at shaft 13. The items are therefore treated by comparison or contrast so far as possible:

1 **Type of rock.** The rock explored at the Bryn Mawr siphon is the same formation as that in the Saw Mill valley cut by the New Croton aqueduct, i. e. the Inwood limestone — sometimes called "Stockbridge dolomite." It is the same also as the other large limestone belts in Westchester county. There are occasional small strips of limestone of another type, but its behavior could not be very different.

2 **Soft material.** "Is any material of this sort" (like that in the New Croton tunnel near shaft 13) "likely to be encountered either in the crushed zone at boring 40 or elsewhere in the limestone belt?"

It is sure to be encountered, especially near hole 40, if that zone is cut shallow. The behavior of the lower portion of this hole is very similar to the described case near shaft 13. The only probability of avoiding it lies in placing the tunnel deep enough to cut more substantial rock. The single hole upon which all this argument is based can scarcely be considered a thorough enough exploration to build up a quantitative statement as to depth or width.

There is no evidence, either on surface or in the exploration holes, of any other such zone on this line.

3 **Depth and extent.** Under the circumstances, the increased depth makes it less probable that so much ground of like behavior would be found. Again, it is not likely that precisely the same conditions would so effectually halt operations or be considered so nearly insurmountable at this time. One of the many serious objections is that the tunnel would have little strength or resistance to a bursting pressure. It must be admitted that if caving ground were penetrated it would prove very difficult to handle with the gravel cover at the depths now considered, i. e. 300 feet or more below the surface.

4 **Water.** "What are the probabilities in regard to the quantity of water to be met in the crushed zone near boring 40? Can any limit be set which it would be extremely improbable that the inflow would exceed, on account of the topography of the country and the nature of the overlying materials?"

There is likely to be much water. Nearly all of the overlying

drift is sand and gravel that is probably saturated and in such condition as to permit easy flow to any lower outlet. It may readily carry 8–10 quarts of water to the cubic foot or about 2 gallons. The area covered by such deposits is about 2500 feet long on the southerly base along the creek and at this margin is approximately 150 feet deep. The northerly margin is variable and reduces in places to 0 feet in thickness. It may, however, really represent 500,000,000 cubic feet of this gravelly material holding 1,000,000,000 gallons of water as a nearly permanent supply.

This overlying material is necessarily a menace of no mean proportions. Every crevice or crush zone remaining unhealed will have water and plenty of it, the inflow being limited only by the size of the cracks and their abundance until the reservoir should be drained. There is no hardpan bottom to act as a dam.

Outside additions to this permanent supply are confined to that received from rain and the stream. The rainfall on the area and immediately available as addition to the underground supply in the lower sands, together with the stream flow, which would probably sink into the sands, if an attempt to drain the underground supply were made, may be expected to furnish additional water at a possible rate of 2500 gallons per minute. How much of all this is available at tunnel level depends wholly upon the openness of structure in the rock. There is nothing else to materially control the permanent and additional supply.

There is evidence in hole 40 of considerable crushing. That means capacity for water circulation, but how much no one can tell. There is also much rotten rock in the same hole. This means that circulation has been easy and effective, but how much now no one can tell. The single hole (no. 40) in the absence of any other corroborative data is not sufficient to base more elaborate or precise quantitative estimates upon.

5 Solubility. What is "the nature of the limestone with reference to its resistance to solution?"

This limestone is, as all limestones are, more easily attacked by circulating water than most other rock types [*see* Rondout Valley]. The Inwood limestone such as occurs at Bryn Mawr is crystalline, often contains much mica and then is inclined to be foliated in structure, and it prevailingly stands steeply inclined. Because of these features in which it differs from the Rondout Valley limestones, it is likely to be more generally affected by decay along the zones permitting circulation than any of the Rondout Valley types.

The Rondout Valley limestones are affected along joint planes, but the effect is almost wholly confined to a simple enlargement of these crevices. In the Inwood an additional effect is the weakening of the sutures or bond between the individual granules resulting in a tendency to weaken the whole mass as far as there is much penetration of seeping water. It would have less tendency to produce openings or caves, but greater tendency to produce a rock that would crumble in the hand or that would gradually assume the condition of a lime sand or a micaceous mud.

As to the effect of water from the aqueduct on fresh portions of this rock, it is certain that the rock would be attacked wherever exposed to direct action. Its method of attack is by solution, and the rate of attack may safely be reckoned as not materially different from that assumed or being established by experiment and experience on the Rondout Valley types.

In the final consideration of the difficulties at Bryn Mawr the engineers have decided to abandon the tunnel plan. It is probable therefore that no additional explorations of direct bearing on the problems of this ground will be made.

CHAPTER XVII

GEOLOGICAL CONDITIONS AFFECTING THE LOCATION OF DELIVERY CONDUITS IN NEW YORK CITY

Hill View reservoir is the terminus of the Southern aqueduct. The Catskill water is to be delivered at this point, just north of the New York city line on the Yonkers side, at an elevation of 295 feet. From this reservoir the water is to be distributed by an independent system of conduits to the principal centers of consumption in lower Manhattan and Brooklyn.

It is believed that distribution can be most economically made and the system be most permanently established by constructing the main trunk distributaries as tunnels in solid bed rock at considerable depth below all surface disturbances.

Preliminary investigations have been carried on by Headquarters department, Mr Alfred D. Flinn, department engineer, beginning in 1908. As the active work of exploration was entered upon Mr William W. Brush, department engineer, was assigned to this special division of the department's work and most of the preliminary exploration borings were planned and finished under his immediate supervision. With the resignation of Mr Brush to take the post of deputy chief engineer in the Department of Water Supply, Gas and Electricity, Mr Walter E. Spear, department engineer, was secured to continue the difficult work of finishing explorations and preparing for construction.

Studies of conditions affecting such a system and explorations designed to test the ground in line with these studies[1] have been made. The work thus far done in an exploratory way has been confined to one main distributary.

Section A. Preliminary geological study

As a preliminary step toward the systematic study of local conditions affecting possible conduits, trial lines were laid out on the

[1] Few engineering enterprises, probably, have been planned with so careful regard for all known geologic conditions. The geologist and the engineer worked alternately on the same problems until, in the opinion of both, the best possible line was selected. It is the writer's belief that so systematic a method has seldom if ever been carried out in engineering work of this kind. On this account, and in part to illustrate some of the preliminary stages in such work, many of the original facts and arguments and suggestions are given without change in the following discussion.

city map from Hill View reservoir to Brooklyn by three different routes. So far as the topography and city development and other engineering considerations could be forseen either route could be used. Studies of all kinds were expected to indicate which would be the most favorable and whether or not it might be advisable to shift even the best one to still more favorable ground. These are shown on the accompanying map which also covers the local geology of the immediate vicinity of the lines [*see* pl. 32].

General questions

When the problem of the practicability of a rock tunnel for distribution conduits was first studied, several general questions were raised which indicate the lines of investigation followed.

1 What is the character of the rock along the projected conduit lines shown at the depths required for such tunnels?

2 Will the rock at moderate depths be such as to permit successful and economical construction of tunnels to be used under the hydraulic pressure due to Hill View reservoir?

3 Does the character of rock in the vicinity of the lines vary sufficiently to materially affect the cost of a tunnel if the lines be shifted approximately 1000 feet either way from those shown on the original map as trial lines?

4 Are the suggested locations of conduit lines adapted from a geological viewpoint to the construction of pressure tunnel conduits, and, if not, what changes in these lines would be advisable?

5 Is the thickness of rock covering sufficient at all points to obviate trouble from open seams and disturbed surface rock?

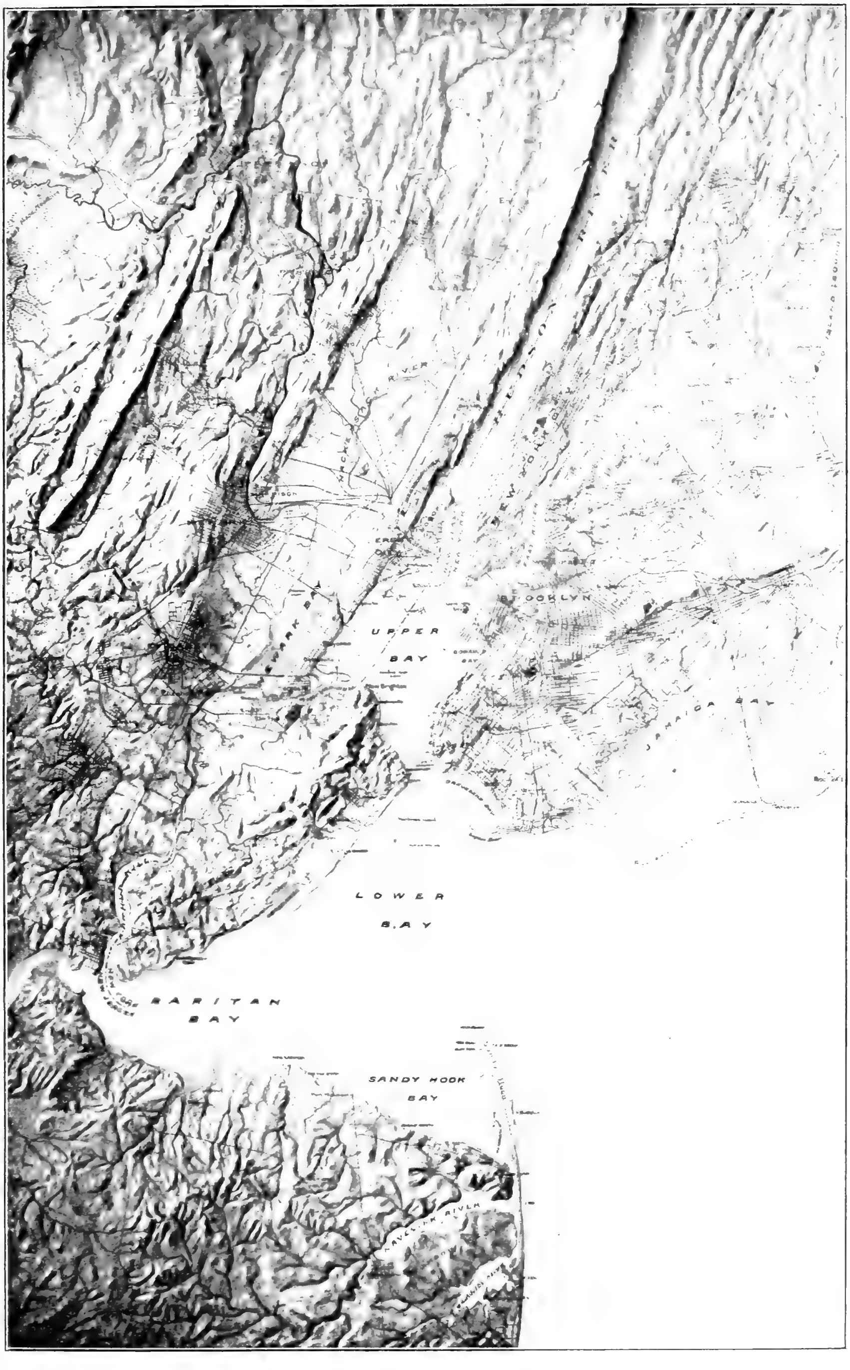
6 What borings and other field investigations should be undertaken to determine the practicability of construction of pressure tunnels along the lines suggested?

In line with this series of questions a thorough geological investigation was begun, the chief conclusions of which are given below.

Geological formations

There are six local formations of sufficient permanence and individuality of character and of sufficient areal importance to be treated as units in this study. These are described in some detail in part 1, but for convenience are briefly listed as follows:

1 Glacial and postglacial deposits of boulders, clay and sand, with silt beneath the rivers.



A relief map of New York city and environs. Reproduced from a model by Howell.

2 Manhattan schist, the most abundant formation, chiefly mica schist with very subordinate hornblende schists, and usually with abundant pegmatite lenses and veins.

3 The Inwood limestone, a white, dolomitic marble when fresh, which shades into impure, micaceous varieties.

4 The Fordham gneiss, varying from a thinly schistose or quartzose rock to a strongly banded or a very massive and much contorted gneiss. The oldest formation of the district.

5 The Yonkers gneiss, an original intrusive granite, now squeezed into a gneiss. Younger than the original Fordham.

6 The Ravenswood grano-diorite or as it might be called in engineering practice, granite; an original, intrusive rock now somewhat gneissoid from pressure. Younger than the original Fordham.

The Manhattan schist, the Inwood limestone and the Fordham gueiss are cut by veins or dikes of coarsely crystalline granite, technically called pegmatite. They are of irregular distribution and do not affect the tunneling operations one way or another.

All the formations older than the glacial drift have been compressed into a series of northeast and southwest folds, and all have as a rule a steep or almost vertical dip. The axes of the folds are not horizontal, but usually pitch downward to the south at low angles. Erosion has developed a series of ridges trending northeast and southwest. The limestone being a softer and more easily eroded rock, almost always underlies the valleys or flats and the river channels. It is certain also that there is some faulting.

Rock at depth

The distribution of geological formations along the proposed lines has been shown on the accompanying map [pl. 32]. In general the kind of rock at tunnel depth will be the same as at the surface as indicated on the map for each point. Such error as there is, arises from two causes: (*a*) Uncertainty as to the exact location of some of the contact lines between two formations (usually due to drift cover), and (*b*) dip and pitch of the strata.

In the first case (*a*) where the drift is particularly heavy, it is sometimes impossible to fix a contact line accurately from surface features alone.

In the second case (*b*) it must be appreciated that nearly all of the formations dip eastward at a very steep angle, so that a formation would usually be found to extend a little further east at depth than at the surface. And also all formations pitch southward, so

that they would be found to extend considerably farther south at depth than their surface outcrops. This angle of pitch is from 10° to 30°.

In nearly all these cases, however, the obscurity of the actual surface boundaries is as great a source of uncertainty as the effect of dip and pitch, so that the boundaries as mapped may be considered sufficiently accurate for this comparative study of the lines.

It is worth noting that the rock at the proposed depths of tunnels would be, as a rule, more substantial than at the surface. But there are several places on all of the lines where the exact condition is unknown at the surface as well as at depth. The chief points of this character will be noted in a later paragraph.

Comparison of lines[1]

A comparison of the three lines submitted as the basis of examination — (*a*) the westerly one, (*b*) the central one, (*c*) the easterly one [*see* accompanying map, pl. 32], as to rock formations likely to be cut by them, furnishes the following figures:

Line A. Going southward from Hill View reservoir

Feet	
6 200	Yonkers gneiss — good rock
1 400	Fordham gneiss
1 400	Probably largely Inwood limestone with one weak zone (at Van Cortlandt lake)
5 600	Fordham gneiss — good rock
2 400	Near contact with limestone, probably in gneiss
1 600	Crossing Harlem river — Inwood limestone
4 000	Inwood limestone — probably fairly good rock
800	Inwood limestone — probably containing bad zone to Speedway
16 400	Manhattan schist (to 135th st.)
2 000	Along contact between schist and limestone
4 200	Inwood limestone with one weak zone (to s. end of Morningside Park)

[1] The statements of quality and extent of certain formations and zones are capable of some modification as exploratory work progresses. Some of these are noted in later sections of this report under special headings, such as The Lower East Side, and The East River-Brooklyn section. For the present purpose, as showing the development of the geologic basis of the project it seems preferable to leave the accompanying comparisons in their original form as presented to the board.

12 800	Manhattan schist probably good quality (to s. end of Central Park)
21 000	From Central Park to East river — no outcrops — mostly Manhattan schists at tunnel depth. Condition largely conjectural[1] — probably mostly good rock with occasional weak zones
6 000	Manhattan island to City Hall, Brooklyn. Containing an unknown[1] zone in the East river and unknown quality of rock in Brooklyn.

Summary of Line A

Feet	
6 200	Yonkers gneiss
7 000	Fordham gneiss
2 400	Contact (probably in gneiss)
12 000	Inwood limestone
2 000	Contact (probably in limestone)
29 200	Manhattan schist (good)
21 000	Estimated Manhattan schist (fair)
6 000	Almost unknown
85 800	total

Line B. Going southward from Hill View reservoir

Feet	
8 000	Yonkers gneiss — good quality
13 000	Fordham gneiss — good quality
6 800	Inwood limestone, probably mostly in fair condition, except at two points (to Cromwell av.)
6 600	Inwood limestone, unknown condition, but probably largely poor (to Harlem river)
600	Inwood limestone — unknown condition (Harlem river)
4 600	Inwood limestone — unknown condition — probably fair (to Mt Morris Park)
800	Manhattan schist, good
800	Probably Manhattan schist — unknown
2 800	Inwood limestone — unknown condition — probably at least one bad zone (to 106th st.)
12 000	Manhattan schist along Central Park — good

[1] Explorations since conducted by the Board of Water Supply have proven the quality and character of the rock floor at these places. For the revised statement on these sections see the special discussions.

Feet	
8 600	To Broadway — Manhattan schist (little known except from tunnels already made)
14 000	To East river, probably Manhattan schist (same as line A)
6 000	Manhattan island to City Hall, Brooklyn — uncertain condition (same as on line A)

SUMMARY OF LINE B

Feet	
8 000	Yonkers gneiss — good quality
13 000	Fordham gneiss — good quality
21 400	Inwood limestone — variable quality
12 800	Manhattan schist — good quality
23 400	Estimated Manhattan schist — fair
6 000	Almost unknown
84 600	total

Line C. Going south from Hill View reservoir

Feet	
6 000	Yonkers gneiss — good rock
17 400	To Webster av.— Fordham gneiss — good rock
5 000	Along contact between limestone and gneiss
9 800	To 138th st.— Inwood limestone with probably two bad zones
1 800	To Bronx kills — along contact between limestone and gneiss — uncertain quality
600	Across Bronx kills — mostly in limestone containing a fault zone — probably bad ground
6 400	Crossing Randall's and Ward's islands and Little Hell Gate. Nearly all is Manhattan schist of good quality
1 000	Crossing Hell Gate — Inwood limestone
1 200	Crossing Hell Gate — Fordham gneiss of good quality
1 800	Astoria point — probably Fordham gneiss of good quality
1 000	Crossing another limestone belt
1 000	To Vernon av.— Fordham gneiss of unknown quality containing one fault zone
7 000	To Nott av.— Ravenswood grano-diorite — good rock
2 800	To Borden av.— Probably Ravenswood grano-diorite.
18 400	To Fort Greene Park Brooklyn — almost wholly unknown but contains probably 5000 or 6000 feet of poor ground

SUMMARY OF LINE C

Feet	
6 000	Yonkers gneiss — good quality
17 400	Fordham gneiss — good quality
6 800	Along contact between limestone and gneiss (questionable)
12 400	Inwood limestone — with several bad zones
6 400	Manhattan schist — probably good quality
3 000	Fordham gneiss — probably good quality
1 000	Fordham gneiss — unknown quality
9 800	Ravenswood grano-diorite — mostly very good rock
18 400	Almost wholly unknown
81 200	total

Tabulated summary — Types of rock formations

	LINE A (WEST)		LINE B (CENTRAL)		LINE C (EAST)	
	Feet	Per cent	Feet	Per cent	Feet	Per cent
Yonkers gneiss	6 200	(7.2)	8 000	(9.4)	6 000	(7.3)
Fordham gneiss	7 000	(8.1)	13 000	(15.3)	21 400	(26.3)
Contact zones	4 400	(5.1)	0	(0)	6 800	(8.3)
Inwood limestone	12 000	(13.9)	21 400	(25.3)	12 400	(15.2)
Manhattan schist	50 200	(58.5)	36 200	(42.6)	6 400	(7.8)
Ravenswood grano-diorite	0	(0)	0	(0)	9 800	(12.0)
Unknown	6 000	(7.0)	6 000	(7.0)	18 400	(22.6)
Total length	85 800	......	84 600	......	81 200	......

Summary of quality

	LINE A		LINE B		LINE C	
	Feet	Per cent	Feet	Per cent	Feet	Per cent
Good rock, 1st grade	42 400	(49.4)	33 800	(40.0)	39 800	(49.0)
Probably fair, 2d grade	30 800	(35.9)	34 800	(41.1)	13 600	(16.7)
Probably poor, 3d grade	6 600	(7.7)	10 000	(11.8)	9 400	(11.6)
Almost unknown	6 000	(7.0)	6 000	(7.1)	18 400	(22.7)
	85 800	100.0	84 600	100.0	81 200	100.0

Argument on choice of line

In judging the quality of rock and its suitability for this conduit the factors of most weight are the same as those repeatedly mentioned in connection with other portions of the Catskill aqueduct line. That is, in brief, that the harder crystalline rocks of the Fordham gneiss and Manhattan schist types wherever known to be

free from fault crushing and surficial weathering are the best variety; that the more heavily buried areas of these rocks, together with those limestone areas that are known to be the most substantial of its class, should be regarded as fair or second grade; that the more obscure areas of limestone and all portions crossing faults or rivers or crush zones in any rock must be regarded as poor or third grade. This rating is based wholly on rock character and without any consideration of cost of construction.

From the above it is clear that line A has more "first grade" rock than either B or C and less "third grade" ground.

Line C has three times as much "unknown" ground as either B or C and less "first" and "second grade" rock.

In other words, the three lines are estimated:

	LINE A Per cent	LINE B Per cent	LINE C Per cent
First grade rock	49.4	40.0	49.0
Second grade rock	35.9	41.1	16.7
First and second grades together	85.3	81.0	65.7
Third grade rock	7.7	11.8	11.6
Unknown ground	7.0	7.1	22.7

In addition to these differences of quality, it appears from a study of the areal geology along the respective lines that a tunnel would pass across limestone contacts from one formation to another six times on line A, four times on line B, and seven times on line C. These may all be considered points of probable weakness.

All of the lines cross belts of well known weakness believed to represent fault zones. Line A crosses three such zones, line B crosses two, and line C crosses at least three.

Furthermore, all of the lines cut limestone for greater distances than seems desirable or necessary. The weakest ground and the most uncertain quality of ground that can be mapped falls within the limestone areas. In this respect line A with 13.9% of limestone ground is preferable to line B, with 25.3% or line C, with 15.2%.

From the above it is apparent that line C is least defensible. Line A has some advantage over both of the others, especially in quantity of first grade rock quantity of first and second grade together, low amount of the known poorest grade and small extent of the so called "unknown" ground.

The chief advantage of line A over line B lies in its much smaller limestone area (12,000 feet *vs.* 21,400 feet or 13.9% *vs.*

25.3%), and the chief advantage of line A over line C lies in its much smaller amount of "unknown" ground (6000 feet *vs.* 18,400 feet or 7.0% *vs.* 22.6%). On these grounds line A is the least objectionable of the three lines proposed.

But it is also clear from an examination of the field, as is shown on the accompanying map [pl. 32], that it is possible to avoid some of these objectionable features or certain parts of them and materially improve the figures by shifting the line to a sort of compromise position between line A and line B. This compromise line, or the trial lines from which the final tunnel line may result, should follow as closely as possible the gneiss and schist ridges and should avoid the limestone areas and known weak zones wherever possible.

Depth of tunnel

The rock formations in general at the required depths are no more objectionable on Manhattan island or in The Bronx than at other localities on the Southern aqueduct. There are weak places and crush zones to be crossed and some of them can not be avoided by any possible manipulation of the line, but these most questionable spots constitute but a small proportion of the whole distance. The depth most suitable must depend chiefly upon the depth necessary at the worst spots.

Comparative cost of construction if lines are shifted

The question is best answered by reference to the geological map. It will be noted especially that the belts of the different rock formations are usually narrow, and that they run nearly parallel to the average direction of the lines. Therefore a shift of line to no great distance would at many points place it within an entirely different formation. It is also notable that all of the lines run along or near the contacts between formations for long distances. At such points a very small shift would wholly change the type of rock and rock quality. Some shifting is desirable.

In general it may be assumed that the limestone belts would be easiest and cheapest to penetrate wherever they are fairly substantial, but they undoubtedly also contain the greater proportion of weak and troublesome ground and must be considered least desirable from the standpoint of maintenance and durability. The gneisses are probably most expensive to penetrate and the schists, medium. Both are more expensive than limestone but both are more likely to prove acceptable for other reasons.

The question of shifting the lines is a complicated one and hinges more upon rock conditions, durability, and location of weak zones, than on any possible cost.

Advisable changes in lines

None of the suggested lines are defensible from a geologic point of view for the reason that a much better one may be obtained by no very serious shifting.

In the general consideration of relative advantages of different possible locations of the line, it is believed that the following large features are of most immediate importance:

1 The ridges as opposed to the valleys.

2 The hard formations as opposed to the softer ones.

3 The crossing of few contacts as opposed to crossing many.

4 The location well within a formation as opposed to location along a contact zone.

It is distinctly preferable from a geologic standpoint (1) to follow the ridges, (2) to keep in the hard formations, (3) to avoid many changes from one formation to another, (4) to keep away from contact zones, and (5) to avoid weak zones, if possible, or cross known troublesome zones at the most advantageous point.

Recommendations of new lines F, G, H, I

The original lines A, B and C are marked on the map in blue [pl. 32]. In addition several trial lines are sketched in yellow, any one of which would give better geological conditions than any of the three original lines. The newly suggested trial lines differ from each other chiefly in the points at which they cross the limestone belts and weak zones. In all of them the central idea has been to follow the gneiss and schist ridges as persistently as possible. All unite at Central Park and are intended to follow Fifth avenue, Broadway, the Bowery and Market street to East river along one of the original lines. North of Central Park they differ from the original lines. The westerly one crosses the Harlem river at 176th street and may be designated line F. The easterly line may also cross the Harlem river at 176th street and may be designated line G; or it may continue southward and cross the Harlem at 155th street. It will then join the first one in the vicinity of 144th street and is called line H. The alternative easterly one which crosses the Harlem at 155th street and follows Seventh avenue to Central Park is line I.

Details of rock conditions along these lines are as follows:

Line F. (Westerly) beginning at Hill View reservoir

Feet	
7 600	Yonkers gneiss — good quality
15 000	Fordham gneiss — good quality
2 000	Fordham gneiss — probably 2d grade
1 200	Harlem river crossing — partly limestone — 3d grade
14 800	Manhattan schist — good quality
1 600	Manhattanville crossing — 3d grade — some limestone
2 600	Manhattan schist — good rock — through Morningside Park
800	At south end of Morningside Park — perhaps some limestone — 2d grade
1 400	Manhattan schist — good — to junction
12 000	Manhattan schist — along Central Park — good
20 600	To East river — Manhattan schist — less known[1] — (fair) (2d grade)
6 000	To Brooklyn "unknown"[1]
85 600	

Line G

Feet	
8 400	Yonkers gneiss — good rock
17 600	Fordham gneiss — good rock

which brings it to the Harlem river where the other line (F) is joined. Although the line is about 1400 feet longer, it avoids some low ground (2000 feet) along the east bank of the Harlem river, some of which may be in poor condition. Total length of line, 87,000 feet.

Line H

Feet	
8 400	Yonkers gneiss — good quality
23 800	Fordham gneiss — good quality — to Harlem river
1 000	Crossing Harlem river — probably fault zone in gneiss
800	Fordham gneiss — good quality
1 000	Limestone — 2d grade
1 200	Manhattan schist — good quality — to junction with the first line (F) at 145th street

From this point the line is the same as F and G. Its chief advantage is the great distance which it has in Fordham gneiss.

Total length of line, 85,600 feet.

[1] Subsequent explorations made by the Board of Water Supply have eliminated this unknown ground. *See* later discussion.

Line I

Feet	
8 400	Yonkers gneiss — good quality
23 800	Fordham gneiss — good quality — to Harlem river
1 000	Crossing Harlem river — probably fault zone in gneiss
4 400	Fordham gneiss — good rock — to 135th street
4 600	Inwood limestone — probably fair — 2d grade
2 000	Inwood limestone — probably poor quality — 3d grade
1 000	Manhattan schist — good quality

At this point the line unites with line F. Total length of line, 83,800 feet.

A tabulation of these figures indicating estimated extent of rock types is given below:

	LINE F Feet	LINE G Feet	LINE H Feet	LINE I Feet
Total length of line	85 600	87 000	85 600	83 800
Length in Yonkers gneiss	7 600	8 400	8 400	8 400
Length in Fordham gneiss	17 000	17 600	25 600	29 200
Length in Inwood limestone and marginal contacts	3 600	3 600	3 400	6 600
Length in Manhattan schist	51 400	51 400	42 200	33 600

Comparative summary of types of formation (Comparative distances are expressed in percentages)

	A	B	C	F	G	H	I
Yonkers gneiss	7.2	9.4	7.3	8.8	9.6	9.8	10.0
Fordham gneiss	8.1	15.3	26.3	19.8	20.2	29.9	34.8
Contact zones	5.1	0.0	8.3	4.2	4.1	3.9	7.8
Inwood limestone	13.9	25.3	15.2				
Manhattan schist	58.5	42.6	7.8	60.0	59.0	49.3	40.1
Ravenswood grano-diorite[1]	0.0	0.0	12.0	0.0	0.0	0.0	0.0
Too little known to classify[1]	7.0	7.0	22.6	7.0	6.9	7.0	7.1

[1] The Ravenswood granodiorite has been proven by later explorations to extend into the territory here marked as too little known to classify.

As a group it is especially noticeable that the new lines F, G, H, I, have a very much lower percentage of contact zones and limestone. The percentages of gneisses have been notably increased, and the unknown and questionable formations have been reduced to approximately the lowest terms.

Estimated summary of quality

	LINE F Feet	LINE G Feet	LINE H Feet	LINE I Feet
Good rock, first grade	53 400	56 800	54 600	49 600
Fair " second "	23 400	21 400	22 400	25 200
Poor " third "	2 800	2 800	2 600	3 000
Unknown[1] (Brooklyn)	6 000	6 000	6 000	6 000
	85 600	87 000	85 600	83 800

[1] All of this rock is now known to be of good quality.

In other words these new lines show:

	LINE F Per cent	LINE G Per cent	LINE H Per cent	LINE I Per cent
First grade rock	62.3	65.3	63.8	59.1
Second "	27.3	24.6	26.1	30.0
First and second grades together..........	89.6	89.9	89.9	89.1
Third grade rock..........................	3.2	3.0	3.0	3.6
"Unknown" ground[1]	7.0	6.9	7.0	7.1

[1] Results of recent boring explorations show that this ground is first grade also.

A comparison on this basis with the original lines A, B, C indicates that these new lines F, G, H, I, make a better showing, especially on first grade rock and that all show decided reduction in the third grade ground.

	A	B	C	F	G	H	I
First grade rock................	49.4	40.0	49.0	62.3	65.3	63.8	59.1
Second grade rock	35.9	41.1	16.7	27.3	24.6	26.1	30.0
First and second	85.3	81.0	65.7	89.6	89.9	89.9	89.1
Third grade rock...............	7.7	11.8	11.6	3.2	3.0	3.0	3.6
Unknown[1]......................	7.0	7.1	22.7	7.0	6.9	7.0	7.1

[1] Now known to be first grade.

On geological grounds, therefore, it is confidently believed that any one of the new lines (F, G, H, I) would give decidedly better results than any one of the original ones (A, B, C). The poor and the questionable and the unknown ground can not be wholly avoided by any possible line, no matter how roundabout. In these lines, approximately as drawn, the objectionable points are reduced to a minimum with almost no increase in total length of conduit. The objectionable portions are also restricted in large part to the

Harlem river, where we already have the experience of the last aqueduct (the New Croton aqueduct) as a guide, and a very few other spots.

General conclusions

Line I is the shortest possible defensible line. Its chief objectionable feature is a rather long stretch, 6600 feet of limestone, from 135th street to Central Park, upon the quality of which there are no data. It crosses the Harlem river fault probably in gneiss. But it crosses the extension of the Manhattanville fault in limestone.

Lines F, G and H are almost equally defensible. Line G is longest, but is in some respects — especially in following the ridge crests — one of the best possible locations.

It should be appreciated that many other matters, such as municipal works already completed or projected, or matters of engineering practice, are likely to make it necessary to modify any line proposed, and that the final line is more likely to be a compromise, considering all interests.

A graphic representation of the comparative merits of the proposed lines is given in plate 33. This is strictly a geologic study. The lines are properly placed on an outline map of the city corresponding exactly to those drawn on the geologic map, plate 32. The geologic formations that each would cut are represented on longitudinal sections which follow each line, and the attitude and structure of each formation are indicated.

Revised lines

Subsequently two revised lines based upon the preceding studies were examined to determine preference. Later one of these, or a slight modification of it, was adopted as the one to be explored. It was soon determined on the same reasoning as was applied to the first group of lines that the most westerly line — the line keeping as much as possible within the gneiss and schist ridges — would be the most likely to give satisfactory conditions. By this method of selection the unknown or untested and doubtful ground was reduced to its lowest limits. It was found that nearly all of the very weak spots could be located by inspection in the northern portion of the line, but south of 59th street the question is decidedly more difficult because of the heavy drift cover. No rock outcrops occur south of 30th street, and one is reduced to the evidence of deep borings.

Graphic Geologic Study of the Alternative Lines for the New York City Distribution Conduit

The attitude of the different formations and their approximate amounts are indicated by longitudinal sections along the alternative lines whose courses are indicated in detail on the accompanying geologic map

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Points for exploration north of 59th street

It was soon evident that extensive exploratory work would have to be undertaken and the following points were selected at which to begin.

1 The Harlem river crossing, where the distribution conduit line crosses the river just below High Bridge [*see* later description]. The only good evidence as to character of rock at this place is from the pressure tunnel of the New Croton aqueduct which crosses the river a short distance above.

2 The Manhattanville cross valley (125th street depression). This is the most important cross depression on the island of Manhattan. It is apparent after a little investigation that the bed rock floor lies deep and that if it were not for the drift filling the tides would surge through this valley making a direct connection between the Hudson and East river. It was the least known as to depth and character of any point along the proposed line.

3 The depression between Morningside and Central Park. At that place limestone on the crest of a pitching anticline reaches farther south than on either side and is more deeply eroded. The other zones of large importance are in southern Manhattan the geology of which is a special study.

CHAPTER XVIII

AREAL AND STRUCTURAL GEOLOGY SOUTH OF 59TH STREET

The necessity for exploration in certain sections of this area can not be appreciated without a statement of the local geology and especially of the revision of both areal and structural geology that the writer has based upon an exhaustive study of all the available drill cores and other data to be found in southern Manhattan, East river and Brooklyn.

Below Central Park there is now little geology to be gathered from a study of the present surface. But as far south as 31st street the bed rock geology is pretty well known from earlier reports and from recent improvements that have exposed the underlying rock. All of this portion is mapped as Manhattan schist except one small area of serpentine at 59th street between 10th and 11th avenues. There is no reason to modify this usage. A careful study of a great number of rock borings from the Pennsylvania Railroad tunnel across Manhattan at 32d street proves beyond question that bed rock is Manhattan schist, including almost all known variations and accompaniments, for the whole width of the island along that line.

Still farther southward the points that have yielded exact information about bed rock are less numerous, and below 14th street are confined to deep borings or an occasional very deep excavation for foundations. Even these sources of information are lacking over large areas. The greater number of borings available are along the water front. Their distribution is such as to indicate that the west side and central portion and southerly extremity of the island are all underlain by Manhattan schist. This is true eastward to the East river at 27th street, and as far eastward as Tompkins square at 10th street and almost to the Manhattan tower of Brooklyn bridge in that vicinity.

To the eastward of these limits, i. e. to the eastward of the line projected from Blackwell's Island to the Manhattan tower of Brooklyn bridge, there is a more complicated geology. The borings of the East river water front are decidedly variable. They are certainly not all Manhattan schist of the usual types. Those most unlike the Manhattan are at the same time most like some varieties

of the Fordham, and indicate that these formations both occur. The lack of any data in the beginning of this investigation except on the water front made it impossible to draw more than very general lines. Drawn in this way, the lines of course are too straight, but it is certain that they indicate more nearly the actual existing areal distribution of formations than any of the maps now in existence.[1] They indicate a southward extension of the Blackwell's Island belt of Fordham gneiss toward the Manhattan tower of Brooklyn bridge. How much of this anticlinal fold of Fordham actually brings this formation to the surface it is impossible to say, but that it may be expected to be encountered along this line is evident.

On the east side a parallel belt of Inwood limestone is indicated and this again is succeeded by a Fordham gneiss area which occupies the rest of the eastern margin. Explorations made along the line of the gas tunnel across East river at 72d street[2] indicates comparatively narrow belts of limestone there in both the east and west channels. The limited width of limestone at these points, together with the occurrence of two strongly developed disintegration zones, seem to indicate rather extensive squeezing out and faulting of this formation along fault planes

[1] In the summer of 1908 the writer was assigned the task of studying in detail the evidences of geologic structure beneath the drift in southern Manhattan. Before any drilling was attempted in the city by the Board of Water Supply, a thorough canvass was made of all previous borings in this district and the cores and records were personally inspected. More than 300 such borings were found in which some of the core could be secured for identification and classification as to formation and condition. Most borings were given no weight at all in the final summary of this evidence unless the rock core or at least fragments of it could be secured. After all of these newly assembled data were tabulated and plotted on the map, it was evident that if the identifications were correct the areal and structural map of southern Manhattan needed extensive revision. A new map therefore was made and presented to the chief engineer of the Board, October 30, 1908. This has been used since as the basis for exploration of the Lower East Side section. This original tabulation and map only slightly modified was published under the *Areal and Structural Geology of Southern Manhattan Island* [N. Y. Acad. Sci. Annals, April 1910, v. 19, no. 11, pt 2]. The extensive explorations of the board have made further revision necessary [*see* accompanying map, pl. 34]. Exploratory boring is still in progress (October 1910) and some slight modifications of boundary lines may yet be made.

[2] This is taken from Prof. J. F. Kemp's description of *The Geologic Section of the East River at Seventieth Street, New York* [N. Y. Acad. Sci. Trans. 1895. 14:273–76].

Base map reproduced from a copyrighted map by E. Belcher Hyde, 5 Beekman street, and here used by permission

Revised Areal Geology of Southern Manhattan Island and the Adjacent Margin of Long Island

This revision is based upon exploratory borings to June 25th, 1910. The heavy blue line marks the course of the proposed pressure tunnel intended to carry the Catskill water to Brooklyn

parallel to the strike. Such movements are capable of cutting out the intermediate limestone entirely from between the schist and gneiss. How much of such modification exists, in the almost total lack of data bearing upon the question, it is impossible to say. The intermediate belt is indicated on the accompanying map [pl. 34], as a limestone area. At one point at least the limestone does occur in the older borings, i. e. on the southeastern margin of the Manhattan pier of the Manhattan bridge (bridge no. 3), at the foot of Pike street.

On the Brooklyn side no formations of this series except the Fordham and its associated igneous masses, such as the Ravenswood granodiorite, have been identified within the area under study. Limestone is reported (Hobbs reference to Veatch) near Newtown creek, a little beyond the eastern margin of the present map.

Structure of the East river area

Manhattan side. In all of the area south of 59th street, structural features are even more obscure than the areal geology.

There is no reasonable doubt but that weak zones will be found as frequently in the Manhattan schist portion of this area as on the line north of 59th street, but they can not be indicated as closely. No cross fault of large consequence can be identified, but there is some evidence of a minor zone that should be encountered on Fifth avenue, in the vicinity of 32d street. The Pennsylvania tunnels and the subway both cross this line and so far as known there were no serious weaknesses developed. There is nowhere any evidence of an important depression like the Manhattanville valley.

It is confidently believed that the problems on this southerly portion of Manhattan are involved chiefly with the longitudinal structures produced by folding and faulting and subsequent disintegration along such zones.

Crossing of East river

From 59th street to the East river there seems to be no reason for a preference between the two lines P and Q.[1] On the Brooklyn side likewise there is no known geological reason for preference. Such basis for choice as is now known relates to the East river channel alone. Since this is at the same time the most difficult section of the line to explore and probably the most uncertain section to estimate as to condition and consequent depth of tunnel, it would be especially useful to be able to make a decisive selection of crossings at once.

[1] For location of these lines *see* map, pl. 32.

Such evidence as has any bearing upon this question has already been used in formulating the interpretation of geologic structure given in the foregoing sections of this report. If the succession and boundaries of formations as outlined are reasonably close to the actual conditions, it would appear that line P (the southerly one just above Manhattan bridge) has some advantage over line Q (near Williamsburg bridge). The chief elements in this advantage are as follows:

1 It would appear that line P might lie wholly within the Fordham gneiss in the East river section, while line Q may cross two contacts.

2 From the evidence of borings made in the East river at 14th street[1] it appears probable that a belt of schist similar to Manhattan schist in quality (whether accompanied by limestone or not there is no direct evidence) lies in the river channel toward the east side and in all probability extends southward in the middle of the river at Williamsburg bridge. This would be cut by line Q. The uncertainties of this association are of sufficient importance to throw the balance of present choice toward line P.

3 If the theory that the East river course is due chiefly to zones of weakness following fractures or faults is true, their possible comparative condition as they cut through different formations must be taken into account. There is little doubt on this point but that, in zones of similar original disturbance, those in the Fordham gneiss have suffered less extensively from disintegration than those cutting either the limestone or schist. Therefore, obscure as it may be, the preference is again in favor of line P.

4 If, furthermore, the course of the river is due to cross faulting or any similar or related displacements or movements, an inspection of the structural map indicates that the controlling zone followed by the river as it crosses line Q must have a general strike northwest, while the corresponding zone that crosses line P strikes east. Of these two types (directions) of fault zones, so far as they may be judged to have influence in the adjacent area, there is no doubt but that the northwest type (the set that has a northwest strike) is both the more common and the more important. If this general tendency is also true here, then on this account also line P may be considered slightly more favored. In reality not much weight can

[1] These borings were made by the Public Service Commission in explorations for subways.

be given to this point since the condition of these faults is not fully known.

5 If, as may well happen, the present East river is displaced[1] from its old channel by glacial drift, so that it is essentially an evicted stream, there may not be as pronounced a channel or as weak ground to cross at such points as at those where the old channel is still occupied. In such case both of these lines are favorable.

6 On the other hand, the crossing of line P is almost a mile nearer to the great Hudson gorges, to which doubtless this portion of the preglacial East river was tributary, and consequently its bed rock channel, if it is the real preglacial channel, may be expected to be deeper and the accompanying disintegration (so far as it may be controlled by this factor) may be expected to reach lower than at points in similar surroundings farther up stream. It is impossible to say how much weight should be given to this objection. It does not seem to be of sufficient importance to fully offset the favorable features indicated in items 1, 2, 3 and 4.

On the basis of these studies line P (the southerly one) near Manhattan bridge was chosen as the site of preliminary exploration promising the most favorable results. Later this was shifted a short distance without introducing any new conditions.

[1] Exploratory borings indicate that such has been the history of the river.

CHAPTER XIX

SPECIAL EXPLORATION ZONES

Exploration by borings[1] and other methods have been made at all questionable or uncertain points along the line. As was expected in the beginning five places have required elaborate exploration and some exceptional conditions have been proven. The original geological investigation based upon surface study as outlined in the foregoing pages served to locate these spots accurately.

These places or zones, now either finished or sufficiently well known to permit accurate statement of geologic conditions, are as follows:

1 The Harlem river crossing at 167th street, where the aqueduct will cross from a ridge of Fordham gneiss beneath the Harlem river, where the whole thickness of Inwood limestone will be cut, to the ridge of Manhattan schist above the Speedway on Manhattan island.

2 The Manhattanville cross valley, a low pass crossing the island at about 125th street. The part explored extends from St Nicholas to Morningside Parks and crosses a zone with very low rock floor in the Manhattan schist.

3 From Morningside to Central Parks. The line crosses the strike of the formations at this point and cuts a longitudinal fault and anticlinal fold which tends to bring the Inwood limestone within surface influence.

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[1] Exploratory work has been in direct charge of Mr T. C. Atwood, division engineer, who has followed all stages of it almost from the beginning. In the later exploratory work an immense amount of detail and a very complex lot of data has accumulated requiring constantly the services of a man with some special geological training. Mr John R. Healey, formerly in the testing laboratory, was transferred to this special field. He is probably more familiar with the multitude of details resulting from boring operations along the conduit line than any one else. Except for the care and good judgment used by these men in preserving data, and the wisdom of the men who planned the line and methods of work before them, much valuable geologic data would have been lost. Notwithstanding the best efforts of the consulting geologist some really critical points escape unless some one constantly on the ground is directly interested in them as a part of the regular responsibility.

4 The Lower East Side zone. On Delancey street east of the Bowery, the line crosses the structure and at this point the whole series of crystalline formations appears. Besides complicated structure there is also exceptionally deep alternation or decay of bed rock.

5 The East river crossing — from the foot of Clinton street to Bridge street, Brooklyn.

1 Harlem river crossing

Geologically the Harlem river between 155th and 200th streets has the same relation to local formations for the whole distance. It flows on the Inwood limestone bed which stands almost exactly on edge, while the east river-bluff is formed by the underlying Fordham gneiss, and the west, by a strong escarpment of Manhattan schist which extends southward throughout the whole of Manhattan forming the backbone of the island.

At the selected crossing a short distance below High Bridge, near 167th street, the schist-limestone contact is in the river and appears to be a low weak spot [*see* detail of record]. The limestone-gneiss contact however is in the flat east of the river bank, near Sedgwick avenue and seems to be more substantial. The structural detail and relations are shown on the accompanying profile and cross section, [pl. 35].

It is observed by examination of the data secured by borings that the limestone formation at this point is exceptionally heavily impregnated with pegmatite dikes and stringers, and that interbedded schist layers are large and numerous.

The weakest spot found lies at the contact between schist and limestone where there is probably some longitudinal displacement.

A similar condition was found at the new Croton crossing 2000 feet farther north. On the whole bad decay does not extend very deep — 150–200 feet.

Several borings have been made and on them is based the only judgment possible of the actual structure and physical condition of rock. In most cases the evidence is easily interpreted for these points. The most weakened spot, as well as the most difficult to interpret in all its detail, is the limestone-schist contact. It is judged that hole no. 17 cut through this contact zone. This boring is located in the river 50 feet from the Speedway (west bank) on the proposed tunnel line which crosses a short distance south of High Bridge. It is known as hole no. 17/C38. Because of the

somewhat unusual quality of material at this place as indicated by the wash and core saved and because of the suggestion it gives

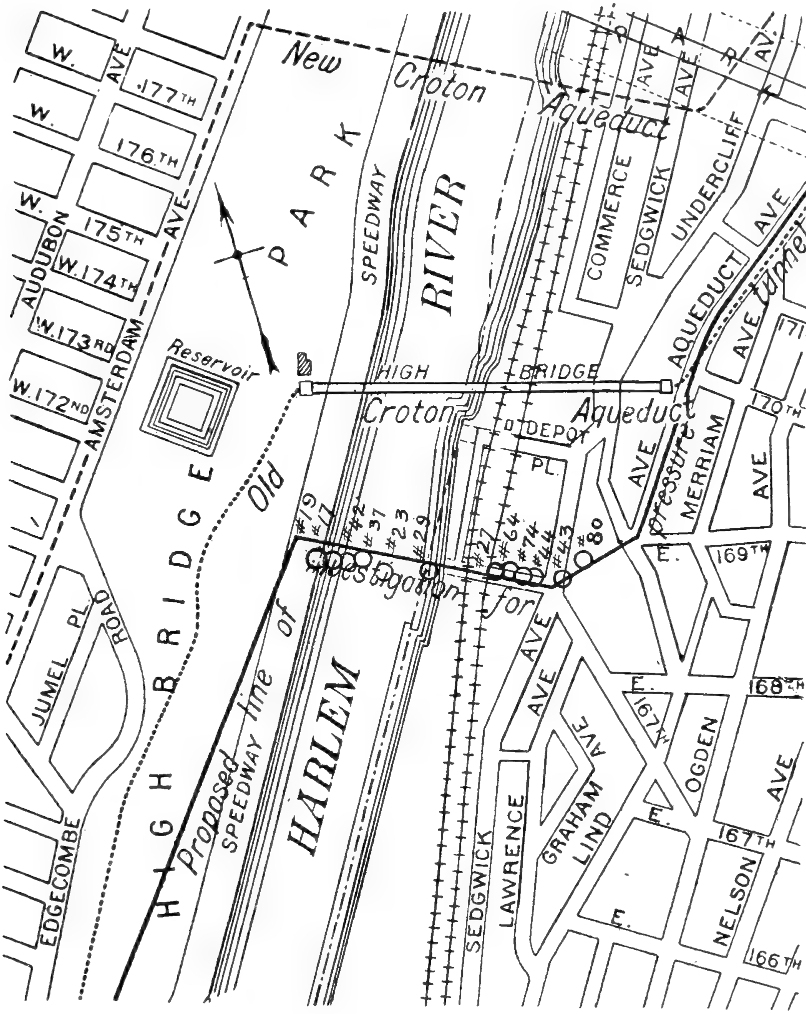

Fig. 38 Key map showing plan of exploratory borings at the Harlem river crossing, location of the New Croton aqueduct which crosses the Harlem in a pressure tunnel and the Old Croton aqueduct which crosses the river on High Bridge

about the structure and condition of rock beneath the river, the record and interpretation notes are given.

Feet	
0— 13	=Water
13— 46	=Black river mud (mostly river silt)
46— 48	=Sand with decayed wood (peaty wood)
48— 70	=Quartz and garnet sand rather clean (glacial)
46— 70	=Lumps of peaty matter coming to the surface at intervals indicating occasional small layers of peat (glacial)
70— 78	=Mixed sand (glacial)
92	=A core of Triassic contact shale (a drift boulder from the Palisade margin). At this point also a piece of Manhattan schist (boulder)
95	=4 pieces of diabase (Palisade trap) from another drift boulder
96.5	=5 pieces of Inwood limestone (boulder) followed by a piece of quartzite and several mixed pebbles indicating glacial drift origin
114—119	=A buff yellow sand with much pearly yellow mica flakes. Effervesces with acid. This shows no foreign matter. It is chiefly residuary decayed rock in place and represents silicious and micaceous limestone. It is decayed, very impure, Inwood limestone
119	=Clay with pieces of flinty quartzite, probably from a small quartzose seam in the limestone
120—126	=Light flaky yellow material. Much pearly mica with earthy matter. Effervesces in acid. Residuary from Inwood limestone
128	=White and drab lumpy residuary matter (kaolin) and earthy substances. Effervesces. A more impure Inwood. Also shows several pieces of core of a porous, rotten limestone. Inwood
129—134	=Reddish brown lumps. Effervesces a very little. Mostly clay but still no foreign matter. Residuary material from a more silicious bed. A few pieces of hard, impure limestone at 133 feet
134	=Pieces of a porous quartz chlorite rock with little lime. Is a leached quartzose rock evidently a sandstone layer in the limestone. Rock belongs to the Inwood formation

Feet

135—143=Dark micaceous matter containing chiefly biotite, a pearly mica, and quartz. Rock is a decayed schist bed=the transition between Inwood limestone and Manhattan schist

143—151=Dark brown micaceous material. Biotite and quartz — chiefly. Rock is decayed schist (transition rock). At 146 feet encountered pieces of a pegmatite veinlet. All pieces except 1 are pegmatitic — the other one is calcareous sandstone, fallen into this lot from the 134 foot level

151—160=Chunks of pegmatite (a vein rock)

151—161=The mica washings continue the same as at 143—151 feet. Rock is a transition schist with pegmatite stringers

164—169=Brownish yellow micaceous matter (loose). Mica, quartz, chlorite, lime. Effervesces

164—173=Many pieces of typical Manhattan schist. A fair amount of core for the conditions. Rock is not so badly decayed but is broken into small pieces. Rock is Manhattan schist of typical character.

Summary

1 The material is chiefly river silt down to 46 feet
2 Lighter glacial deposits 46—78 feet
3 Heavy bouldery drift 78—97 feet
4 Uncertain (insufficient data) 97—114 feet
5 Residuary micaceous decay products from Inwood limestone 114—135 feet
6 Decayed transition schist bed with some lime, but chiefly like the Manhattan schist 135—161 feet
7 More calcareous schist 161—164 feet
8 Typical Manhattan schist 164—173 feet

Interpretation

1 Foreign matters, glacial and recent deposits, continue to a depth of between 97 and 114 feet.
2 Rotten formations (residuary matter) in place begin at least as high as 114 feet. There is no foreign material below that point except grains that have fallen into the hole from above.

3 More solid rock begins at 164 feet.

4 The upper portion of the rotten rock (114–35 feet) is calcareous enough to belong to the Inwood limestone formation. The lower 9 feet (164–73 feet) is typical Manhattan schist. The intermediate ground 135–64 feet is transition variety.

5 The drill has cut the contact between Inwood and Manhattan formation.

6 If this identification of the badly decayed matter is correct, the contact at this point dips steeply eastward, i. e. it is overturned.

7 Both types of rock are shown to be extensively decayed.

8 The worst (deepest) decay zone probably lies still a little farther east, and follows the dip of the micaceous limestone near the contact.

These conditions are indicated on the accompanying cross section [*see* pl. 35].

The conditions indicated by this one hole are consistent with those known for the New Croton aqueduct tunnel 2000 feet farther north where, according to the engineers' drawings, the formations also are overturned. Fifty feet of decayed rock is shown in this hole. The contact is undoubtedly decayed considerably to a depth of more than 200 feet below water level.

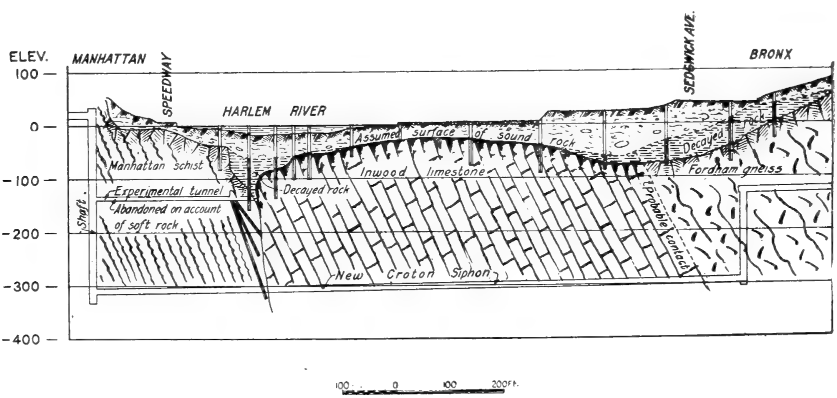

Fig. 39 Harlem river crossing — New Croton aqueduct

Another boring put down to test conditions at still greater depth nearby explored the rock to −442.7 feet. Because of the information it gives about the deeper bed rock, a summary of the record based upon examination of the material is given:

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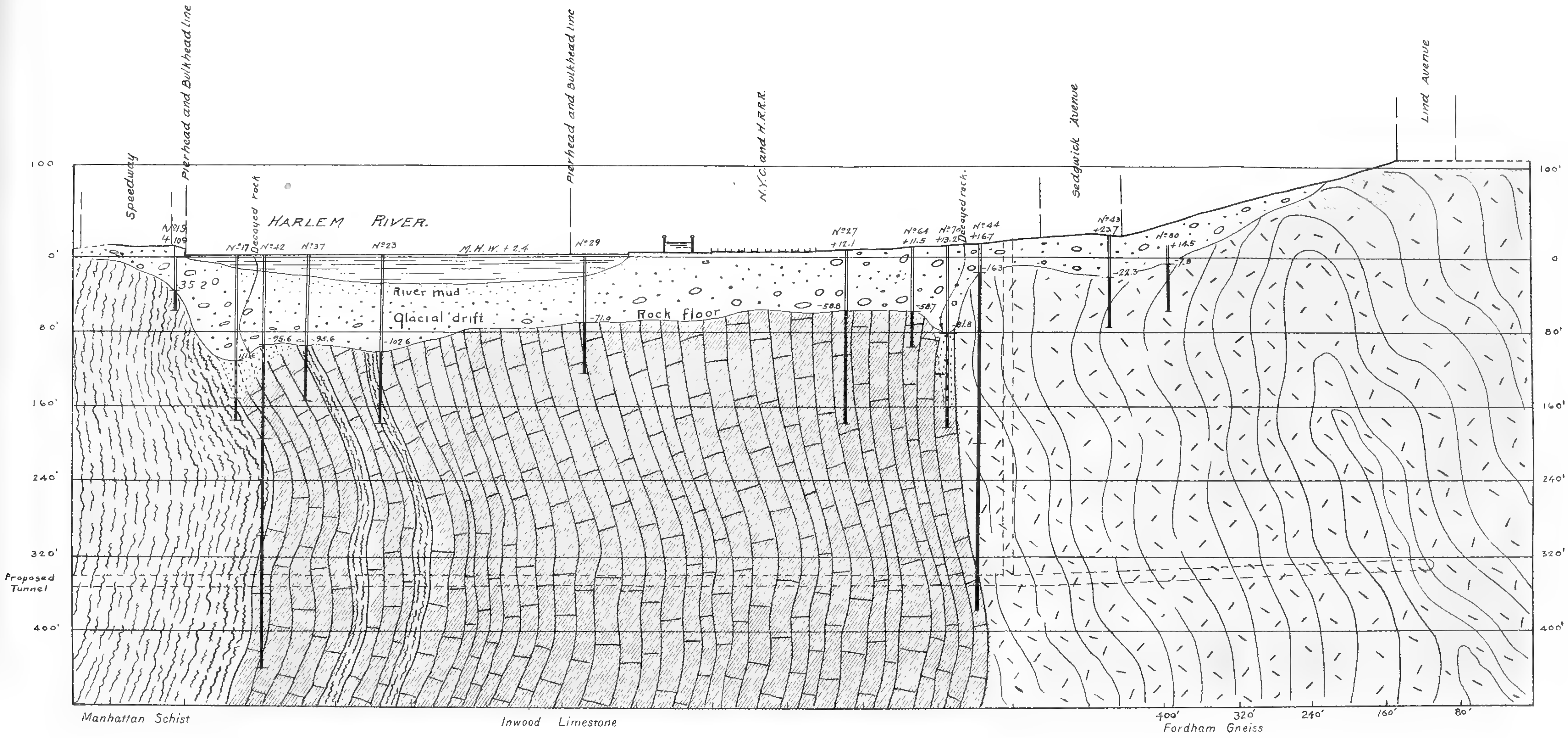

Geologic cross section and graphic interpretation of the exploratory borings made for the New York City Board of Water Supply at the site of the proposed pressure tunnel beneath the Harlem river, reaching Manhattan at the foot of 171st street

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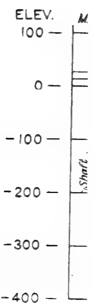

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Hole no. 42 (75 feet from Speedway, 25 feet east of hole no. 17)

Feet	
0 to −94.1	River muds and various types of drift similar to hole no. 17
−94 to −96	Iron cemented sand — both drift sand and local angular material
−98 to −127	Micaceous clay — residuary decayed matter — with choppings of calcite, quartz, mica and chlorite representing weathered Inwood limestone
−127 to −135	Core — Inwood limestone (impure)
−135 to −149.5	Pegmatite
−149.5 to −197	Inwood limestone — typical — standing almost vertical in upper portion but changing to about 45° and farther down to 60°. Good sound rock
−197 to −241	Manhattan schist — of typical sort — and in sound condition, but becoming somewhat more broken and altered near the bottom. Dip about 60°–80° and even more. Average probably 75°–80°
−241 to −295	Manhattan schist — typical — dip variable but mostly above 70° to vertical — some pegmatite — fractures are at high angle. Rock sound
−295 to −302.5	Pegmatite
−302.5 to −442.7	Inwood limestone — typical — good quality — dip 70° to very flat — one piece not over 35° but mostly obscure

An interpretation summary is as follows:

Feet	
0 to −94	River muds and drift filling (glacial and recent)
−94 to −96	Transition to residuary matter
−96 to −127	Residuary matter and badly decayed Inwood limestone
−127 to −197	Inwood limestone
−197 to −302	Manhattan schist
−302 to −442.7	Inwood limestone

Geologic cross section. The accompanying cross section [pl. 35] embodies an interpretation of all the data secured in the Harlem river. It is now known that the limestone is overturned

slightly at both contacts. The nature of these contacts makes it seem probable that there is very little of the limestone squeezed or cut out by movement. Therefore this crossing gives a fairly accurate measure of the thickness of the Inwood. This is approximately 750 feet. No section about New York city is more accurately determined.

2 Manhattanville cross valley

In northern Manhattan the schist ridge which forms the backbone of the island and has a relief of more than 100 feet, is cut across by a prominent valley that extends from the Hudson at 130th street eastward to the Harlem Flats and East river. This valley is nowhere more than 25 or 30 feet above the sea level and is drift filled. Previous to the recent boring explorations of the Board of Water Supply its true depth to rock floor was unknown. The few borings recorded, however, indicated a depth of more than a hundred feet. One such boring at 129th street and Amsterdam avenue is reported as penetrating 109 feet from surface without touching rock. Another of similar results is located at 125th and Manhattan streets where a depth of 204 feet failed to touch rock.

Besides determining rock floor in the present case, it was important to determine rock structure and conditions. It appears from surface features that this cross valley probably follows a fault zone along which there has been weakening of the rock and consequent disintegration and decay. If this is so it would be advantageous to find the limits of it and determine what displacement effects were produced. It has been surmised by all students of local geology that such cross faults may lift the blocks on the south side of them, one of the chief indications being the fact that in spite of a strong southerly pitch in all the formations they do not rapidly disappear below sea level.

The accompanying profile and explanatory section indicates the principal results of exploration [*see* pl. 36]. Badly crushed ground has been found in the holes near the north end of Morningside Park but the rock, when found, is not very badly decayed. The rock floor is very low, almost 200 feet below sea level at the lowest. It appears that if the drift were stripped off from this valley the Hudson and Long Island sound would unite across the Harlem Flats and Manhattanville forming a channel and outlet much deeper than the present East river course.

The glacial drift of this valley is prevailingly fine modified drift some of which is probably stratified and fairly well assorted.

This is more strikingly true of the southerly extension of this low ground southward along Morningside Park. A very deep and prominent preglacial stream came down from the gap between Morningside and Central Parks.

It is not yet proven that the fault has really raised the Morningside block. At least if there is such displacement it is not of sufficient amount to bring up a different formation at any point yet examined. It would be possible for the limestone to be brought up to the surface, but except for a few pieces of interbedded limestone no evidence has been secured. The occurrence of this, however, is thought to indicate proximity to the limestone contact.

General geologic conditions established. Fourteen borings have been made for the special purpose of determining exact conditions. On the data of these holes there are several features now established beyond question that were originally given only as probabilities. The most important of these may be enumerated as follows:

1 A very deep cross valley is now proven between 123d and 126th streets, and its profile can be plotted.

2 A part of this ground is badly broken, as if belonging to a fault zone, but most of the floor thus far tested is not in bad condition, i. e. it is not very badly crushed or decayed.

3 The drift cover in this cross valley is more than 200 feet deep over a distance of more than two blocks on the proposed line (from 123d street to Manhattan street).

4 The limestone contact lies more than 300 feet east of the proposed line at this Manhattanville cross valley.

5 At 121st street the limestone-schist contact stands very steep and is probably slightly overturned. This is indicated by the data of hole no. 33.

6 The contact line approaches nearer to Morningside Park in passing southward, touching the park between 110th and 113th streets and the contact is probably not overturned in this southerly extension.

3 Morningside to Central Parks

The contact between Inwood limestone and Manhattan schist follows nearly parallel with the Morningside Park boundary on the east side, but, because of its form, actually touches the park only at the southern end between 110th and 113th streets. At the north end it lies off more than half a block to the east. The Manhattan schist forms an escarpment because of its more resistant

character and this eastward facing cliff and slope forms Morningside Park. St Nicholas Park, farther north, from 128th to 155th streets has the same structural relations. In both cases the present escarpment stands back from 200 to 500 feet from the actual contact.

As the formations all pitch southward and are pretty closely folded, the higher formations gradually appear and at 110th street another parallel ridge of Manhattan comes in above the limestone in the trough of the next syncline to the east. This forms the north end of Central Park and from this point southward Manhattan schist is continuous. But between the Morningside belt of schist and the Central Park belt at 110th street lies an anticline of Inwood limestone also pitching southward and gradually passing beneath the schist which encroaches upon it in a long wedge until a few blocks farther south it passes wholly beneath the schist, which from that point is continuous.

This anticlinal wedge and its accompanying structures and rock condition was the subject of some detailed exploration.

The records of a few drill holes together with an interpretation of all the data will serve for the present purpose.

The most important borings are summarized below:

a Hole no. 3 on 113th street, 232 feet east of Morningside Park East

Surface elevation+42.6 feet

Rock floor at depth of 81.5 feet=el. –38.9 feet.

Material:

0–19 feet=to el.+23.6 feet=soil and mixed drift

19–79 feet=to el. –36.9 feet=modified drift. Assorted sands and silts

81.5–94.58 feet=to el. –54 feet=Inwood limestone. Typical and in good condition

b Hole no. 7. On 113th street, corner of Manhattan avenue

Surface elevation+38 feet

Rock floor at depth of approximately 165 feet=el. –127 feet

Material:

0–85 feet=to el. –47 feet=modified drift

85–165 feet=to el. –127 feet=sand with much more clay, part of which may be decayed rock

165–240 feet=to el. –202 feet=disintegrated rock ledge. Some micaceous type believed to be the transitional facies of the schist-limestone contact

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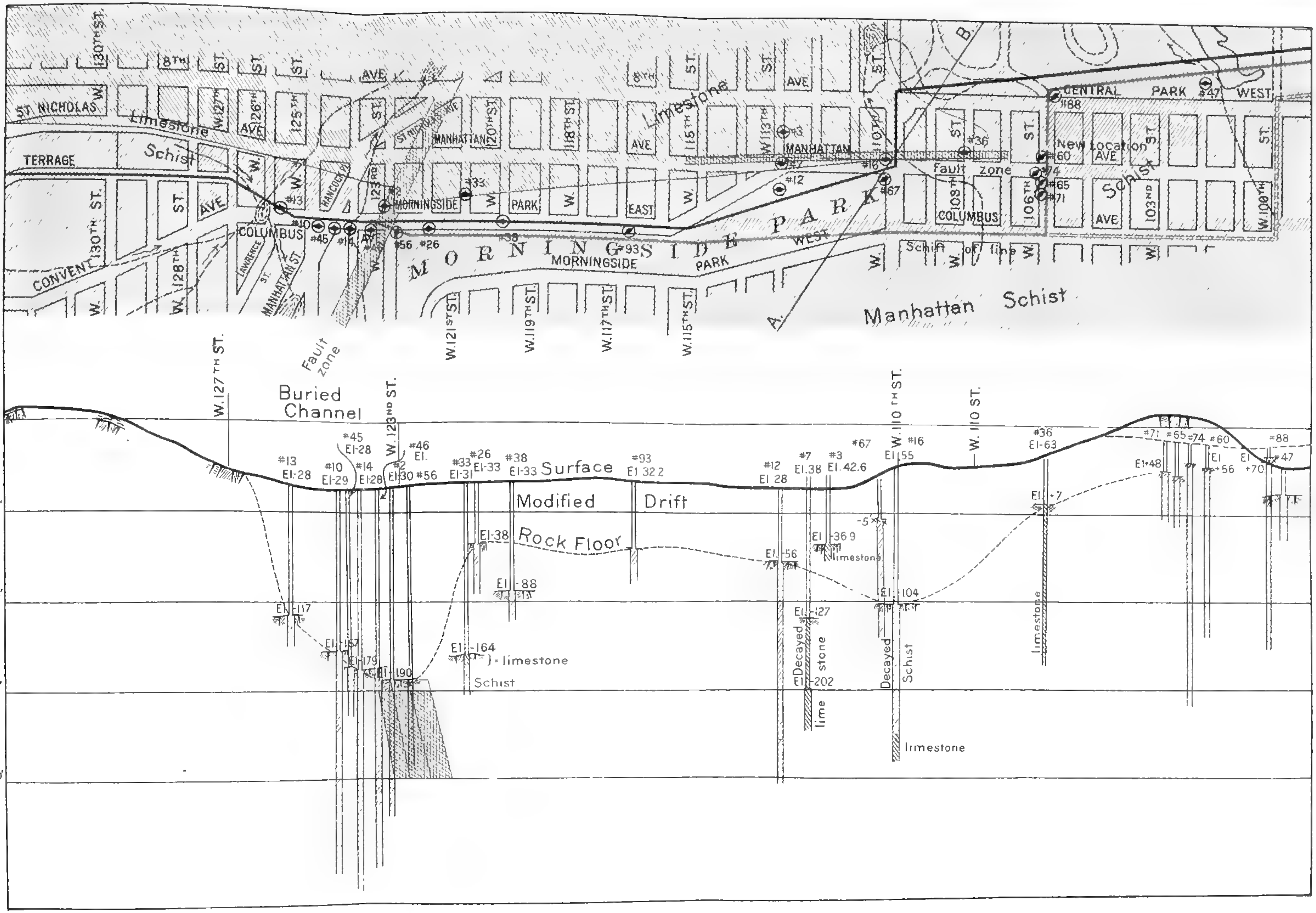

Geologic detail of the Manhattanville-Morningside section showing the alternative lines studied, the locations of exploratory borings, the two principal crush zones and longitudinal profiles

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242–280.71 feet=to el. –242.71 feet=Inwood, very coarse type of limestone. Poor core showing. Much broken

c Hole no. 12. In Morningside Park at 113th street

Surface elevation+28 feet

Rock floor at depth of 84 feet=el. –50 feet

Material:

0–26 feet=to el.+2 feet=mixed drift

26–84 feet=to el.–56 feet=modified drift

84–335.15 feet=to el.–307.15 feet=Manhattan schist, typical with considerable pegmatite. But all good sound rock, not much broken and standing at about 65°–80°

d Hole no. 16. Corner of Manhattan avenue and 110th street

Surface elevation=+55 feet

Rock floor at depth of 159 feet=el.–104 feet

Material:

0–44 feet=to el.+11 feet=filled ground and mixed material

44–159 feet=to el.–104 feet=fine sands and silts interpreted as chiefly modified drift. Much of it very fine and the lower portion rather micaceous and angular throwing a little doubt on the exact line of demarcation between drift and residuary matter

159–161 feet=to el.–106 feet=core of Manhattan schist

171–186 feet=to el.–131 feet=decayed rock in place, some micaceous type, coming out as mud

186–228 feet=to el.–173 feet=micaceous reddish mud with variable amounts of angular quartz grains. Certainly residuary decayed rock

228–270 feet=to el.–215 feet=similar residuary matter less highly colored passing from reds into grays and coming out as soft material

270–305 feet=to el.–250 feet=grayish micaceous and quartzose residuary matters. With much silvery mica and chloritic grains near the bottom

305–335 feet=to el.–280 feet=Inwood limestone, *core*, ordinary type. No more recovered above this point except for 2 feet between 159 and 161 feet

e Hole no. 36 at 108th street and Manhattan avenue

Elevation of surface+63 feet

Rock floor (decayed) at depth of 55 feet=el.+8 feet

Depth to solid core=248 feet=el.–185 feet

Material:

0–55 feet=el.+8 feet=modified drift (fine silts)

55–155 feet=to–108 feet=micaceous soft material with broken sand=decayed micaceous rock

155–215 feet=to–152 feet=reddish mud of similar constituents. Is decayed rock colored by iron

215–240 feet=to–177 feet=transition to more grayish and greenish soft matter

240–245 feet=to–182 feet=greenish mica rock=a decayed chlorite, mica quartz, schist layer

248.33–254.25 feet=from el.–185.35 to–191.25 feet=chloritic Inwood limestone

A summary of these data gives:

0–55 feet=drift

55–245 feet=decayed rock ledge

248–254 feet=solid rock ledge (limestone)

f Hole no. 2 at 123d street, 100 feet east of Morningside Park East

Surface elevation+30 feet

Rock floor at depth of 220 feet=el.–190 feet

Material:

0–13 feet=to el.+17 feet=soil and mixed drift

13–220 feet=to el.–190 feet=modified drift=mostly assorted sands and silts

220–245 feet=to el.–215 feet=soft decayed schist

245–355 feet=to el.–325 feet=Manhattan schist much broken — poor core recovery — worst material at about 225–240 feet and again near bottom. Formation evidently much shattered and considerably decayed

g Hole no. 33 on 121st street, 300 feet east of Morningside Park East

Surface elevation+31 feet

Rock floor at depth of 195 feet=el.–164 feet

Material:

0–25 feet—soil and mixed drift

25–195 feet=to el.–164 feet=drift, mostly modified drift= assorted sands and fine silts

190–195 feet coarser material—pebbles

195–200 feet=to el.–169 feet=Inwood limestone, coarser limestone of usual type

200–237 feet=to el.–206 feet=Manhattan schist

Ordinary type and in good condition [for interpretation *see* later comments]

Condition of the limestone schist contact. The finding of Inwood limestone above the Manhattan schist in hole no. 33 at 121st street east of Morningside and the fairly sound condition of both types raises the general question of the condition of contact zones as compared with fault zones.

There are three important facts to consider bearing on this case: (1) The contact zones are commonly weaker than either formation alone and (2) at this particular point an abnormal relationship is shown by the overturned strata (the limestone lying above), and (3) the fault zones are always weak and extensively decayed.

Because of the abnormal position of the limestone here, lying as it does overturned, a weaker more pervious rock upon a more substantial and less pervious one, it appears to be reasonable enough to find the limestone and schist fairly well preserved, under conditions where a vertical or a normal position would have encouraged decay because permitting a more ready circulation.

But there is a further conclusion that seems allowable, i. e. the fault or crush zones are more extensively decayed than the simple contact or transition zones. And contrariwise, where an especially extensive decay is encountered, it probably is to be associated with a crush zone due to fault movement rather than with any other structure.

A further inference seems allowable from the data of these holes. It is probable that these fault zones do not follow the contacts or bedding exactly but cut across at low angles, sometimes coinciding with the contact lines and sometimes falling wholly within the limestone or the schist.

Great depth of decay at south end of Morningside Park. The finding of approximately 150 feet of decayed rock in hole no. 16 and of nearly 200 feet of similar type in hole no. 36, all so rotten that the material came up as a mud, raises a very difficult question as to the conditions that make such extensive decay possible.

Hole no. 7 (113th st.) shows extreme decay to elevation –204 feet
Hole no. 16 (110th st.) shows similar condition to elevation –250 feet
Hole no. 36 (108th st.) shows similar condition to elevation –185 feet

These three holes showing similar condition of very deep decay are located almost exactly in line. Nothing on either side of this line is in so poor condition.

Consideration of these conditions can not fail to raise certain questions of interpretation.

1 It would appear that at least one of these borings (no. 7) is near the schist-limestone contact. May they all lie then in the weakened contact zone?

2 It is true that at least one core (also from no. 7) shows a badly broken condition. May they all lie in a fault zone?

3 There is no reasonable doubt but that the geologic structure at the south end of Morningside Park is that of a pitching anticline carrying the limestone beneath the schist in its southward extension.

May the excessive decay be due to this relation?

The evidence on these various possibilities is not complete enough to make a conclusion very reliable. But there are two or three factors that have a bearing and they unite pretty well in supporting one view.

These factors are: (*a*) the exact alinement of these three holes, (*b*) the crushed core of hole no. 7, (*c*) the overturned position of the formations 10 blocks farther north, (hole no. 33), together with the apparently normal position in hole no. 16.

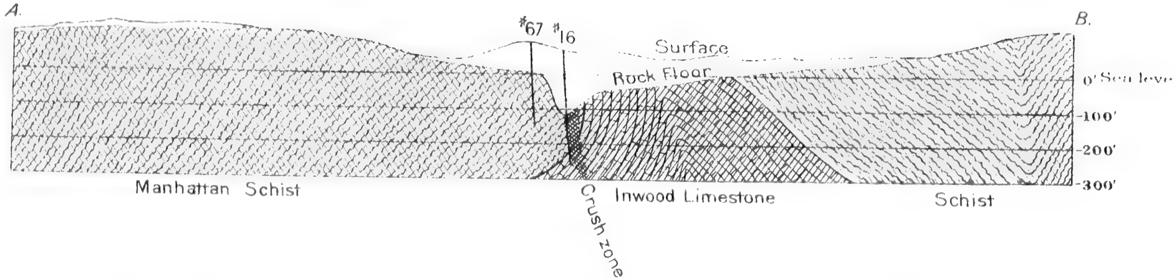
All of these points are consistent with the opinion that we have to do here with the crush zone of a fault, one that runs rather straight and one that follows not far from the contact of the schist and limestone at this point. And it is probable that the weakness follows the west margin or limb of the limestone anticline as it plunges beneath the schist. Such evidence as there is favors this view.

If that is true, then one may expect that the worst ground is not very wide, but that one probably can not go entirely around it. The best line would run south far enough to get above the limestone, and then cut across the weak zone nearly at right angles. It is certain that the ground improves southward.

Later borings are all confirmatory of the conclusion that the weakness is narrow and dies out rapidly southward as soon as the limestone passes well beneath the schist. No bad ground has yet been found on 106th street where the tunnel will probably be located.

4 The East river section

Preliminary studies of southern Manhattan and the East river led originally to the conclusion that the portion of the East river forming the great eastward bend from 32d street to Brooklyn bridge probably has a simpler geologic structure than those portions farther north or south. It was long known that the structure at Blackwells Island is very complex and involves all of the local formations in close folding and considerable faulting. But there seemed to the



Geologic cross section of the line A-B near 110th street, from Morningside Heights to Central Park, showing the anticlinal structure and location of the crush zone along which deep erosion and decay have been found

writer after studying all available data, good reason to believe that the river leaves this belt when it bends to the eastward and that it is in this part a displaced stream. In that case the East river could be flowing upon a floor of gneiss of a most substantial sort.

Explorations are now complete on a line that crosses the river from Clinton street, Manhattan, to Bridge street, Brooklyn. All borings have found good sound rock at moderate depth and all are comparatively shallow holes. Their positions and depths and rock types are tabulated below.

No. of boring	Distances in feet from Manhattan pier head line	Approximate interval in feet	Elevation of rock floor below mean sea level in feet	Type of rock	Formation
9	0	....	—48	Granodiorite	Fordham
21	225	225	—65	"	"
53	350	125	—72	"	"
32	525	175	—71	"	"
50	695	170	—76	"	"
34	860	165	—74	"	"
41	960	100	—81	"	"
39	1 070	110	—67	"	"
67	Brooklyn side near bulkhead	....	—75	Banded gneiss	"

The rock floor is thus very uniform as to contour across the East river at this point. No water course yet explored about Manhattan island has shown so simple conditions including as it does sound rock and shallow channel. The rock varies a good deal but is prevailingly a coarse grained granodiorite. In places it is very garnetiferous and at others is banded or micaceous, but all belong to the Fordham formation as a general formational unit.

Borings in the East river made by the Public Service Commission both above and below this point found an occasional deep hole with excessive decay to more than a hundred feet without securing sound core. At this crossing the deepest point in the channel to sound rock floor is 81 feet.

It is certain from these results and from others in adjacent ground that the East river does not occupy in this part of its course the original stream channel. It has been displaced (evicted) by glacial encroachment and has never been able to reoccupy the lost course. Therefore, instead of the river following a belt of lime-

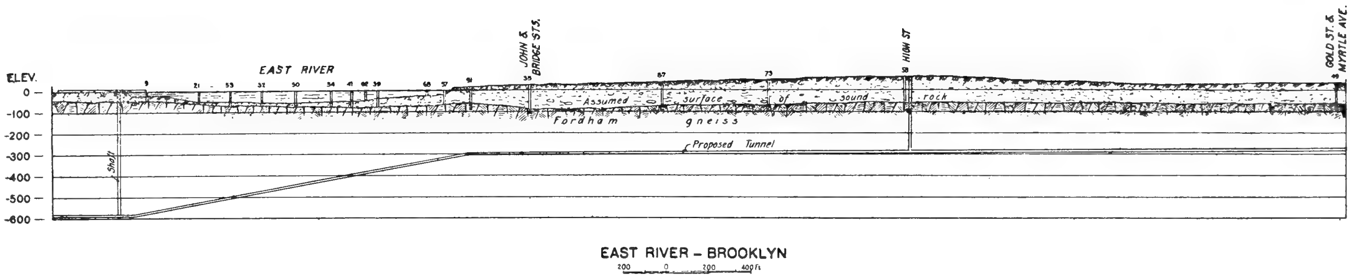


Fig. 40 Profile of surface and rock floor as indicated by borings from the foot of Clinton street, Manhattan, to Gold street and Myrtle avenue, Brooklyn. The rock floor is chiefly some variety of the Ravenswood granodiorite intrusive in the Fordham gneiss formation. It is one of the soundest rock types in New York city and the profile is more uniform than usual in any of the local formations. It is clear that the East river in this part of its course has no rock channel.

stone around this big bend as was formerly supposed, it follows no rock floor structure at all but is in this part of its course wholly superimposed. The original valley lies farther to the west cutting through the midst of the Lower East Side where the more complicated geologic structures again prevail.

Borings at intervals of 500 feet have now been made on the Brooklyn side of the East river to Gold street and Myrtle avenue. So far as developed there is no other formation than the Fordham and the associated granodiorite within the area covered. The rock floor is remarkably uniform at an elevation of from –70 to –90 feet. The accompanying section shows the relations of rock floor to present drift surface [fig. 40].

STRUCTURAL GEOLOGY OF THE LOWER EAST SIDE, DELANCEY AND CLINTON STREET SECTION

The proposed distributary conduit turns from the Bowery eastward on Delancey to Allen street, thence on Allen to Hester street, thence on Hester to Clinton street and follows south on Clinton to the East river. This so called Lower East Side section includes one of the most complicated geologic structures in New York city. The most complex portion extends from Christie street on the west side to Monroe street on the east. Between these two points all of the crystalline rock formations form a series of parallel beds that are folded together so closely that they stand practically on edge.

This general fact and the approximate location of the several beds have been proven for some time. But the more exact structure, with the depths to which the beds go before bending upward again, and the distances through each one are only approximately determined by the exploratory borings to date. The chief uncertainties arise from the fact that the beds are also faulted and the dips of the fault planes are not yet determined and the amount of displacement is unknown. The difficulty of forming a good estimate of the obscure points is greatly increased by the fact that no rock of any kind is to be seen at the surface. Judgment is based wholly on borings.

There are other important questions covering the zone, such as: (1) depth of serious decay, (2) location and width of these decay belts, (3) general physical condition of the rock at certain levels, (4) length of tunnel that will cut each formation, (5) best depth for safe construction.

The accompanying geologic cross section [pl. 38] embodies an opinion of the structural relations of the different formations. It is

offered as the writer's interpretation of borings to date, and its more direct use is as a working basis and guide in conducting explorations. The western half of the section may be accepted as more accurate in minor detail than the eastern.

To simplify the section it is drawn on a line crossing this zone more directly than the conduit as laid out, i. e. through holes 28 and 5 and the borings are projected along the strike of the formation to the section line. All the data therefore are used and the structure is not distorted, but the distances through each bed would be greater on the conduit line because it runs more diagonally across the formations.

Borings. The following tabulation of borings and interpretations upon them forms the basis of the present ideas of structure and quality of rock on the Lower East Side. The borings are given in order from west to east, and all points are neglected except those bearing upon geologic structure.

28 The Bowery and Delancey street
Surface elevation 40.5 feet
Rock floor –71 feet. Rock is Manhattan schist, and has been penetrated to –91 feet

78 Delancey street west of Christie
Surface elevation 41.4 feet
Rock floor –101.6 feet. Rock all typical *Manhattan schist* — at about 60°

224 and 301 North side of Delancey street west of Christie street
Surface elevation 42 feet
Rock floor at el. –99 feet
Manhattan schist to el.–330 feet
Inwood limestone to bottom at el. –395 feet

229 Northeast corner Delancey street and Christie street
Surface elevation 43 feet
Rock floor at el. –108 feet
Manhattan schist with very poor core recovery to el. –260 feet
Inwood limestone to bottom at el. –360 feet

84 Delancey street east of Christie
Surface elevation 41.8 feet
Rock floor –135 feet. All badly decayed schistose rock, of same type — no effervescence — red color — soft as cheese to –204 feet

227 is a reoccupation of this same hole 84
Inwood limestone was found below el. –250 feet to the bottom below el. –300 feet

63 Delancey street west of Forsyth
Surface elevation 43.2 feet
Rock floor –141 feet. Inwood limestone at 80° — very low saving of core

72 Delancey street 121 feet east of Forsyth
Surface elevation 42.6 feet
Rock floor –122 feet. Very noncommittal rock, one piece very good Fordham and the rest not decidedly any special type
Classified as Fordham on this basis. Same behavior to bottom –109 feet

81 Delancey street and Eldridge
Surface elevation 41.7 feet
Rock floor –98 feet. Rock is typical Fordham gneiss — banded and very micaceous — to bottom –123 feet

225 North side of Delancey street east of Eldridge street
Surface elevation 40 feet
Rock floor at el. –74 feet
Fordham gneiss in good condition with interbedded limestone at bottom at el. –550 feet to bottom at el. –671 feet

25 Delancey street between Eldridge and Allen streets
Surface elevation 40.6 feet
Rock floor –68.3 feet. Banded Fordham gneiss — sound rock — dip about 45°

233 South side of Broome street east of Allen street
Surface elevation 42 feet
Rock floor at el. –96 feet
Fordham gneiss with good core recovery down to el. –200 feet
This hole is also known as 302 under a subsequent contract

85 Delancey street
Surface elevation 38.7 feet
Rock floor –82.3 feet. Banded Fordham gneiss — dip about 60° or less — bottom at –171 feet

223 Grand street east of Allen street
Surface elevation 41.2 feet
Rock floor at el. –123 feet
No core recovered in the first 140 feet
Inwood limestone with dip averaging about 45° from el. –303 feet to bottom at el. –710 feet
Splendid core recovery

208 Hester street east of Allen street
Rock floor at about –145 feet
Inwood limestone with structure at about 60 feet — 70°
Enters fairly sound rock and has continued to over 600 feet with dip as low as 20°, toward the bottom

15 Delancey street near Ludlow
Surface elevation 35.7 feet
Rock floor –106 feet. Pegmatite and Inwood limestone, massive and bedding obscure

217 Southwest corner of Ludlow and Hester streets
Surface elevation 36 feet
Rock floor at el. –128 feet
Inwood limestone for more than a hundred feet succeeded by thin strips of gneiss and limestone interpreted as interbedded Fordham

222 Hester street west of Essex street
Surface elevation 36.6 feet
Rock floor at el. –130.4 feet
Fordham gneiss with interbedded limestone showing fair core recovery below el. –400 feet
Dip of rock structure about 60°

216 South side of Hester street between Essex and Suffolk streets
Surface elevation 33 feet
Rock floor at el. –167 feet
Interbedded limestone and Fordham gneiss with a dip of approximately 45° to el. –625 feet
Core recovery was variable

8 Norfolk and Grand streets
Surface elevation 35.8 feet
Rock floor –130 feet. Rock a close grained schistose limestone, Inwood, showing foliation at about 45°

231 South side of Hester street opposite Norfolk street
Surface elevation 32 feet
Rock floor at el. –103 feet
Decayed gneiss and no core recovery to el. –300 feet. This boring was continued as no. 303 under a subsequent contract and carried to el. –525 feet with only a small recovery of Fordham gneiss

218 South side of Hester street east of Norfolk street
Surface elevation 31 feet
Rock floor at el. –183 feet
No core recovered in upper 300 feet
Interbedded limestone in Fordham gneiss below el. –550 feet to bottom

77 Hester street near Suffolk [*see* 202]

202 Hester street west of Suffolk
Surface elevation 30.5 feet
Rock floor –99.5 feet. Rock all decayed to great depth
Manhattan schist to –470 feet
Fordham gneiss –470 feet to bottom at –577 feet
Believed to cross fault plane

213 Hester street 85 feet east of Suffolk street
Surface elevation 33.3 feet
Rock floor at el. –116.7 feet
The rock is Fordham gneiss of the black and white banded type, with dips varying from 30° to 80°. For a very short distance at el. –275 feet dips of 10°–15° were recorded
Core recovery very good

11 Hester and Clinton streets
Rock floor –204 feet. Badly disintegrated and no core to –279 feet. Unusual rock, identified as a mica schist of obscure structure (not typical). Some calcareous portions.

At first this was thought to belong to the Manhattan formation, but it is probably a schistose and rather unusual facies of the Fordham series. This hole was subsequently reoccupied and deepened as no. 220 under another contract with the result that an interbedded series of gneisses and limestones was shown to a total final depth reaching el –660 feet. Rock cores indicate dip of about 60°.

201 Clinton street between east Broadway and Henry street
Surface elevation –31.3 feet
Rock floor –133.7 feet
A schistose variety of Fordham gneiss with associated interbedded limestone

219 Northwest corner of Clinton and Madison streets
Surface elevation 26 feet
Rock floor at el. –214 feet
Fordham gneiss and interbedded limestone
Good core recovery below el. –400 feet

232 Southeast corner of Clinton and Madison streets
Surface elevation 25 feet
This hole was reoccupied as no. 304 and penetrated the rock floor at el. –353 feet
The boring has not progressed far enough to recover identifiable material for rock formation

211 East side of Clinton street south of Madison
Surface elevation 24
Rock floor elevation uncertain because of failure to recover core and the obscurity of the material washed up. Interbedded limestones and gneisses of Fordham series were recognized from el. –336 feet to el. –680 feet

51 and 207 Henry street between Clinton and Montgomery
Surface elevation 32.4 feet
Rock floor –214.6 feet. All badly decayed to great depth mostly believed to belong to limestone and underlain by interbedded Fordham gneiss at about –345 feet

221 Clinton street near Monroe street
Surface elevation 22 feet
Rock floor at el. –116 feet
Fordham gneiss mostly very sound, with some thin interbeds of limestone at about el. –500 feet
Dip of structure 45° to 80°

226 West side of Clinton street, north of South street
Surface elevation 10 feet
Rock floor at el. –37 feet
Fordham gneiss in very sound condition showing structure at 60° to 90°

305 Southwest corner of Clinton and South streets
Surface elevation 9 feet
Rock floor at el. –50 feet
Fordham gneiss with structure at 70°

4 Montgomery and Madison streets
Surface elevation –32.5 feet
Rock floor –65.5 feet. Fordham gneiss of granodiorite type

Two borings are of special interest and significance, and because of the rarity of such details being recorded they are given more fully below.

Each one is of great depth and indicates conditions decidedly different from the commonly accepted behavior for Manhattan Island.

Special interpretation of hole no. 202, on Hester st. near Suffolk st. This is one of the very deep borings, on the proposed distributary conduit, put down to investigate the character, condition, and structure of the rock through which the proposed tunnel would pass.

A summary of the data secured, together with an interpretation of conditions encountered follows:

1 *Boring record* (*summary*)

Elevation of surface = +30.5

a Glacial drift

0–123 feet. Soil and various types of glacial drift

b Residuary matter of local decay

130–150 red micaceous mud

c Disintegrating rock ledge too much decayed to furnish core

150–190 disintegration matter from pegmatite and associated ledge

190–214 quartz, hornblende, chlorite, mica, disintegration sand

d Decayed ledge rock capable of furnishing an occasional core

214–224 core — several pieces of coarse feldspathic, quartz mica rock

224–237 core — several pieces of core with much green mica

237–255 Cuttings and disintegration sands with much green mica

255–277 Pegmatite cuttings

277–305 Yellow clays and quartzose disintegration sands and cuttings

305–314 Core-pegmatite

314–388 Gray quartzose disintegration sands

402–447 Coarse quartz and mica disintegration sands and finer quartz-mica, hornblende-chlorite cuttings that do not look badly decayed. The rather surprising thing is their failure to core

447–463 Core — four pieces of schistose rock with white mica and garnet, nearly vertical, and three fragments of pegmatite

464–497 Cuttings only

497–512 Core — a quartz biotite, feldspar schistose rock that is rather easily disintegrated but does not show bad decay. Resembles the Fordham formation more than the Manhattan

512–531 Disintegration sand and cuttings containing abundant pearly mica

531–547 Core. Many fragments of coarse quartzose and micaceous limestone, interbedded type

e Ledge furnishing sound core

558–559 Core from quartz vein

573–588 Close textured quartz — feldspar — mica rock. Two pieces with foliation structure at about 60°

597–607 Typical banded Fordham gneiss with good structure, dip about 60°, common black and white or gray and white bands in good solid condition. Thin sections and microscopic examination of the rock indicate bottom perfectly crystalline, well interlocked, foliated rock with constituents in good sound condition

Summary of record and formation assignment

Feet

0–123 Soil and drift

130–150 Residuary matter of local decay

150–500 Ledge rock considerably decayed — micaceous schist passing into quartzose schist or gneiss mostly badly decayed, but occasionally giving core

500–531 Quartzose rock resembling the Fordham rather than the Manhattan

531–547 A quartzose limestone probably interbedded with the Fordham

558–607 Fordham gneiss, the lowermost part of which is very sound

Discussion of meaning of this hole

There were three rather puzzling features about the data of this hole at the time it was made: (1) The fact that Fordham gneiss was penetrated at a point so far to the west; (2) the finding of a small bed of quartzose limestone in the midst of other types; (3) the finding of both schistose rock closely resembling the Manhattan and typical Fordham gneiss in the same hole with so little space between.

As to these points, the first one needs little comment. That is, it seems to mean that much more of this Lower East Side ground be-

tween Madison on the east and the Bowery on the west belongs to the Fordham than at first supposed. This very much improves the outlook for safe and easy construction.

The second one, i. e. the finding of limestone at 531 feet is probably an interbedded limestone bed and not a part of the large Inwood formation.

The third point, i. e. the finding of schists and gneisses in the same hole introduced more difficulty of interpretation. This difficulty was considerably increased by the fact that the ledge is so badly decayed and so broken up in the drilling that no typical material for identification could be secured in the upper portion. There is no doubt as to the finding of Fordham in the lower portion. Later explorations support the conclusion that the whole belongs to the Fordham series.

When this boring was first made, the schistose portion was thought to be the Manhattan formation, and the limestone could then be Inwood. Subsequent exploratory work at other points has proven that the Fordham itself shows such schistose facies rather commonly where associated with the interbedded limestones. This is now the accepted interpretation for the whole eastern half of the Lower East Side belt covered in the present discussion.

There probably is some faulting. But whether the fault plane dips east or west and how much the total movement is has not yet been developed. This, however, is a more vital question than would at first appear, for if the fault dips east the ground to the west of it is probably all Fordham of good quality and will be easily explored, whereas if the fault plane dips to the west the whole west side for several blocks is much more uncertain. It is probable that the majority of the rock lying west of it will be of better quality than found in this hole.

Interpretation of hole no. 207 (old no. 51)

On Henry street midway between Clinton and Montgomery

Drill boring no. 207 has been put down to a depth of more than 655 feet (approximately –633). The material is of unusual quality and behavior and therefore seems to require special study with a view to reaching a correct interpretation. The most essential points of the drill record are given below.

1 *Explanatory record.*

a Soil and glacial drift (surface to depth of 195 feet)

Surface to 190 feet=sands, gravels, clays of unusual variety

190–195 feet=reddish clay

b Residuary matter — mostly decayed rock (195–247 feet)

212–240 feet micaceous clay — judged to be residuary because of the abundance of mica and the scarcity of worn quartz grains and rarity of foreign particles

c Decayed rock ledge preserving original structure representing interbedded limestone (247–377 feet)

247 feet=decayed rock ledge with white blotches showing traces of structure

256–330 feet=oxidized—mostly red and brown clays and sands from disintegration of decayed rock in place

349–351 feet=gray micaceous clay

251–377 feet=quartzose and micaceous disintegration sands and calcareous clays that effervesce in acid. Much pearly mica

d Decayed rock ledge representing Fordham gneiss formation (377–489 feet)— no calcareous matter

377–489 feet=quartz and pearly mica disintegration sand varying from coarse to fine and mostly of very light buff color

e Disintegration matter from a chloritized hornblendic gneiss of too little cohesion to withstand the grinding action of a drill of so small cross section (13/16 inch). (487–532 feet)

487–532 feet=fine dark colored disintegration sand composed chiefly of quartz, chlorite and mica, the material is of same composition as the cores secured just below

f Core from more substantial rock — a hornblendic gneiss sound enough in part to withstand the drilling process and save a small amount of core (532–655 feet)

532–537 feet — 9 pieces of a green chloritic foliated rock (14 inches –) structure 70°–80° — a close textured rock much oxidized and hydrated

537–551 feet — 8 small pieces and other fragments of same rock

551–566 feet — 17 pieces and several fragments same rock. All close texture and highly chloritic

581–596 feet — 2 small pieces (two very brown, hard pieces) are probably not natural — "drillite," i. e. a peculiar product formed by the drill when it is run too dry and partly fuses fragments of rock and flakes of iron from the drill into a compact rocklike mass

611–631 feet — 14 pieces same chloritic foliated rock. Two pieces of "drillite"

One piece of fresh rock — a gray gneiss of rather worn texture

646–655.5 feet — 16 pieces of — a white and black and red blotched rock — a garnetiferous gneiss. The rock is not a common type but a similar variety is sometimes seen along the margins of the granodiorite intrusions and belongs to the Fordham gneiss series.

Rock is fairly sound and for the size of core the saving is good. (3 feet)

2 *Deflection test.* A deflection test on this hole indicates that the drill has not departed more than 5° from the vertical.

3 *Behavior of drill.* It has been possible to drive the casing down after the drill without reducing the size and without enlarging the rock hole to a final depth of 625 feet.

About half of the water fed into the machine is lost — 10 gallons per minute being fed and 5½ gallons recovered.

The hole filled after each pull up as much as 100 feet with matter that either ran in from a crevice or was furnished by disintegration of the walls or was simply the settling of matters held in suspension during operation. These settlings or corings, as the case may be, were of large amount (100 feet ±) when the drill was cutting far below the casing and small in amount (5 feet) when the casing was driven down near to the bottom. This matter then increases as the hole is deepened again below the casing.

Cutting and progress are rapid and easy.

4 *Examination of the rock.* (*a*) Hornblendic gneiss. A microscopic examination of the green hornblendic gneiss shows that the rock is not badly crushed and that the different original grains are well interlocked. But the more easily affected mineral constituents are very generally decayed and have become especially modified on their surfaces where they interlock with other grains. The matter developed is mostly chlorite — a mineral that is very soft and one that in this case fails to furnish a very firm bond between the grains. A disrupting force exceeding the strength of this soft mineral therefore, such as drilling with a small bit or forcing the drill, causes the grains one by one to roll out or break apart and furnish the suspended matter that seems to be so abundant in this hole.

b The rock below 646 feet. This is a very unusual type of rock, the petrographic character of which need not be taken up here. It appears to be simply a contact variety, such as sometimes is devel-

oped along the margins of the granodiorite masses where they cut into the banded Fordham gneiss.

The essential feature of the rock is its fresh and sound character. This rock is not decayed.

5 *Interpretation*

a Drift

The glacial drift and soil cover the bed rock at this point for a depth of at least 195 feet.

b Residuary soil

Decayed residuary matter of local derivation is detected at 212 feet.

c Bed rock

The decayed matter still preserves the bed rock structures in a sample taken at 347 feet. From this point downward there is decayed rock ledge gradually becoming more substantial

d Formations represented

After bed rock is reached the first 100 feet is so altered that identification is not certain. At 350 feet, however, the calcareous nature of some of the material is observed, and on this ground largely it is believed that an interbedded limestone layer is penetrated down to about 377 feet.

From that point (377 feet) the material is very silicious and not at all calcareous and the core when obtained is distinctly gneissoid. This lower portion below (377 feet) is therefore judged to be typical Fordham gneiss.

The bottom material is sound but a very rare variety for this formation.

e Character of contact

Normally the interbedded limestone lies conformable to the structures and beds of Fordham gneiss. The structure in such pieces as show it indicated a dip of about 70-80°. Therefore the formation must stand very steep. But, so far as can be seen in the fragments secured, there is no direct evidence of a fault contact or anything abnormal. The extremely deep alteration of the rock is the chief unusual feature. It seems to require a better chance for water circulation than is natural in the undisturbed rock of either formation. For this reason, I am of the opinion that there has been movement in this zone that weakened the rock enough to encourage water circulation.

The formation dips west in normal manner at about 75 degrees.

f Condition of the rock

That the upper 100 feet of ledge is very rotten can not be denied, but it is certain that this lower portion of the hole is not in so bad condition as the low saving of core would lead one to think. The grains are affected by chloritic alteration in such manner that they can not resist much disrupting force. The small diameter of drill used subjects the whole core to enough strain to cause the gradual pulverization of the rock. This affects both the core that has been cut loose and the hole wall that is further subjected to the thrashing of the drill rods. A larger size core would make a very much more encouraging and fair showing.

There may be an occasional small seam so badly decayed that it is encouraged to run or cave under such treatment. But there is absolutely no evidence that slumping or caving is common or even likely on any considerable scale.

The material that partly fills up the hole when the drill is pulled up is believed to be in considerable part the settlings of suspended matter which during the agitation of drilling is distributed through the rising column of water. The reduction in volume (10 gallons being fed and only 5½ gallons being recovered) due to rock porosity is favorable to such behavior of the loosened material.

SUMMARY OF LOCAL GEOLOGY.

Formations. Only three formations are represented in the rock floor of this section. These are the regular crystallines characteristic of all southeastern New York.

1 Manhattan schist

2 Inwood limestone or dolomite, and

3 Fordham gneiss, including the Ravenswood granodiorite as a special intrusive member, and an unusually strong development of the interbedded limestones and associated schistose facies.

These formations have their usual relation — the Manhattan above and youngest, the Inwood intermediate, and the Fordham underneath and older. These simple relations, however, are much complicated by dynamic disturbances of more than usual violence so that the series is thrown into folds so close that the individual beds stand almost on edge. In addition lateral thrusts of that same time or later have broken the strata and faulted them in several places. This complicates the structures still more, and, since the

amount of displacement is in no case fully known, makes the structures in some minor details impossible to accurately interpret at this stage of the work.

Fault zones. As nearly as the material recovered can be classified and accredited to the above three formations it has been done. On this identification together with the location of points of greater decay the chief fault zones are drawn. The chief ones are judged to be thrust faults but it is possible that one is a normal fault. Such a combination is comparatively rare where the zones are so close together, but it seems to best explain the relations of beds as interpreted from identification of the present borings. It is not an unknown association though in this region. It probably indicates faulting in two different periods. This is consistent with the observation also that some of the fault breccia ground is not much decayed while others are badly affected. Probably the later movements have not allowed rehealing of the crevices and they are then the lines of chief circulation and alteration.

It is clear, upon examination of the section as now known,[1] that both the eastern and western belts of limestone are too thin and narrow to accommodate the whole Inwood limestone. The Inwood normally is a formation of about 750 feet or more in thickness. It is therefore certain that a part of it has been cut out by squeezing or faulting. If by faulting then there would be expected to be in each case somewhat greater decay than usual along the fault zones. The fact therefore that such decay zones are found along one margin of the limestone bed in each case leads to the conclusion that faulting is the true cause. In some cases thrust faulting would be required to produce the result and leave the beds standing in their present relations [*see* pl. 38].

INTERBEDDED LIMESTONES OLDER THAN THE INWOOD

The finding of limestone beds within the Fordham gneiss formation so persistently in the Lower East Side borings is one of the geologically interesting and rather surprising results of recent exploration. All of the borings in the Fordham gneiss area in this particular district except those near the East river have shown some limestone.

The individual beds vary greatly in thickness, ranging from only a few inches to many feet. Because of the steepness of the dip of the beds and the obscurity of this factor in many borings it is sel-

[1] October 1910.

dom possible to compute their thickness closely. It is probable that most of them are not over 5 to 10 feet thick, although rarely a thickness of 25 or 30 feet may be represented. It is certain also that a considerable number of separate beds are penetrated. All attempts to correlate the limestone cores from different adjacent holes have so far met with little success. No doubt some of those cut at great depth in one hole correspond to others cut higher in an adjacent hole. But the differences in thickness are notable even in the best cases, and it is evident that little dependence can be put upon uniformity of thickness as a factor in correlation. The foldings and crumplings, and shearing have probably affected the limestone members of the series more than any others. Limestones in comparatively thin beds are, under such conditions, especially liable to excessive thinning and thickening through recrystallization and rock flowage. It is not at all likely that any single bed at present preserves much uniformity of thickness. In some places they are pinched out entirely while in others they may attain a thickness much greater than the original. It is possible also that some of them are repeated by folding. Whether or not this is true in the Lower East Side section no one can tell. On the whole there is no direct evidence of repetition in this way. After making allowance for all possible duplication there is still a surprisingly large number of limestone interbeds represented — probably 10 — a larger number in succession than is known anywhere else in southeastern New York [*see* pl. 38].

In petrographic character these so called limestones are all essentially very coarsely crystalline dolomitic marbles or silicated dolomites of still more complex constitution. Occasionally a very pure carbonate rock is represented that corresponds in appearance very closely indeed to the best grades of the Inwood, but there is no doubt whatever of the true interbedded relation of these limestones. Their similarity of appearance to the Inwood in certain facies is so great that from the petrographic evidence alone one could not differentiate them. Their fixed relation however is unmistakable and they belong unquestionably to an entirely different geologic formation from the Inwood — a much older one, in fact the oldest known formation in southeastern New York — equivalent to the Grenville series of the Adirondacks and Canada. The silicated facies contains many of the common products of metamorphic processes. Recrystallization has produced micaceous minerals such as phlogopite and chlorite in abundance. Original and secondary quartz is

plentiful. Serpentine, tremolite, diopside, actinolite, occasionally chondrodite, and rarely metalic ores are found. In many cases the limestone passes by transition gradually into a more and more silicious facies until the rock is simply a silicious Fordham gneiss with quartz, mica and feldspar as the essential constituents. There is seldom a sharp break between the two types. Many pieces of apparently simple gneiss will show effervescence of a carbonate constituent with acid.

The silicious beds of the gneiss series proper immediately associated with the limestone layers are also more silicious or more micaceous than the average Fordham. They are essentially micaceous quartzites and mica schists and the rock generally lacks the strong black and white banding that characterizes the common or typical Fordham gneiss of other localities. It is this facies of the gneiss which most closely resembles certain facies of the Manhattan schist, and when the rock is much decayed or badly broken or is ground to pieces by the drill the confusion is still greater. The micaceous variety may readily be mistaken for Manhattan schist and the accompanying limestone may equally be mistaken for Inwood.

The occurrence of interbedded limestones of the Fordham series is probably more common than was formerly believed. They are not very often seen on the surface areas of gneiss. Possibly this is largely due to differential weathering and erosion which together tend to obscure those portions of outcrops where such beds may occur. But the type is well known. Mr W. W. Mather in his *Geology of the First Geological District* [1843] interpreted certain limestones in the Highlands as interbedded in their relation to the gneisses there. Later workers were inclined to disregard his views on this point and there was a marked tendency to place all limestone occurrences in one formation. Some of the geological maps have been made in this way. The writer, however, raised the issue again in an article published in 1907 under the title "Structural and Stratigraphic Features of the Basal Gneisses of The Highlands,"[a] N. Y. State Museum Bulletin 107. It is certain that there are interbedded limestones with the gneisses in The Highlands. More recently, the writer has recognized similar occurrences in the typical Fordham gneisses of The Bronx, New York city. The vicinity of Jerome Park reservoir is the best locality in all southeastern New York to see this interbedded development. The best exposures are at the following places.

1 In the margin of Jerome Park reservoir at 205th street.

2 East side of Villa avenue north of Bedford Park boulevard.
3 East of the Concourse between 198th and 199th streets.
4 South side of 196th street both east and west of the Concourse.

One of these occurrences was known to the geologists of the United States Geological Survey [New York City, Folio No. 83] but it was regarded by them as an infold of the Inwood. An examination of all four occurrences will convince one that they are not infoldings. In at least two cases the structure accompanying the beds is actually anticlinal instead of synclinal.

These occurrences in the vicinity of Jerome Park reservoir are essentially the same as those disclosed by the borings of the Lower East Side. In spite of its thick drift cover — 50 to 200 feet — there are more limestone interbeds known there than in any other area of similar size in the region. It is entirely possible that a thorough exploration in certain other belts might reveal an equally elaborate development elsewhere.

The substantiation of interbedded limestones as a prominent element in certain facies of the gneiss series and their association with typical silicious gneiss layers with transitional relation emphasizes still more the strictly sedimentary origin of at least some portions of the Fordham series. Other observations lead to the conclusion that they are the oldest members of the series and that the igneous associates, of which there are many, are all younger intrusives.

One of these later intrusives is the Ravenswood granodiorite which cuts into the eastern margin of the Lower East Side, forms the floor of the present East river channel at the point of aqueduct crossing and continues as far as explorations have been carried into Brooklyn.

Structural detail of Lower East Side

What the detailed structure of the Lower East Side is, it is impossible to say at the present stage of exploratory development. Its general features of structure are fairly clear. The Manhattan schist, which is the universal floor rock of the central and western parts of Manhattan island, extends only a short distance east of the Bowery. The Inwood limestone comes to the surface of the floor at Christie and Forsyth streets. An anticlinal ridge of gneiss comes up at Eldridge and Allen streets. Then a syncline of Inwood limestone is pinched into the next three or four blocks and from

this point eastward — from Norfolk street nearly to the East river — the Fordham gneiss with many interbeds of limestone forms the rock floor.

As much of this detail as it is now possible to classify has been included in the accompanying drawing, plate 38, in which special attention has been given to the interbedded limestone occurrences.

In view of the fact that a tunnel is finally to be constructed through this section which will cut the whole series of formations and structures at a depth probably between el. –600 and –700 feet, it is clear that much greater accuracy of geologic interpretation is soon to be attainable on many of the more obscure points. Because of this also it is not advisable to attempt a detailed structural cross section at the present time. It can very well await the more complete data to be gathered during construction of the tunnel.

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City of New York
BOARD OF WATER SUPPLY
CATSKILL AQUEDUCT
GEOLOGIC DETAIL OF LOWER EAST SIDE
ELIZABETH
THE BOWERY
DELANCEY ST.
BROOME
CHRYSTIE
FORSYTH
ELDRIDGE
ALLEN ST.
ORCHARD ST.
LUDLOW ST.
ESSEX ST.
NORFOLK ST.
SUFFOLK ST.
GRAND ST.
HESTER ST.
CANAL ST.
EAST BROADWAY
MONTGOMERY ST.
HENRY ST.
MADISON ST.
JEFFERSON ST.
MONROE ST.
CHERRY ST.
WATER ST.
SOUTH ST.
CLINTON ST.
ELEV.
Drift surface
Glacial Drift
Rock Floor
Decayed Rock
Manhattan Schist
Inwood Limestone
Fordham Gneiss Series with occasional limestone bed
Probable Sound Line
Fordham Gneiss Series mostly granodiorite
Fordham Gneiss Series with many narrow Interbedded Limestones
The lower profile line is intended to mark the limit of rock decay as interpreted from borings. Each prominent depression probably indicates a crush zone belonging to a fault.
Schist = S -
Limestone - L - LS. -
Gneiss - G -
Recovery over 25% shown thus
Recovery under " " "
No Recovery " "
NOTE - Borings are projected parallel to strike on line joining hole #28 and hole #5. Approximate bearing of strike is N 25° E
200 0 200 400 Ft
OCTOBER 18, 1910

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CHAPTER XX

THE GENERAL QUESTION OF POSTGLACIAL FAULTING

WITH ITS BEARING ON THE PERMANENCE OF ENGINEERING STRUCTURES.

Evidences of postglacial faulting and other recent movements have of late attracted a good deal of attention. The experience of San Francisco in the exceptionally disastrous earthquake and fire, traceable directly to earth movements of the nature of faulting which dislocated or injured the water conduits rendering them useless, is fresh in the minds of men everywhere who have public responsibilities of this kind. If displacements are occurring at the present time, or if any related movements are continuing, or if there is evidence of recent disturbances of this sort in this region, they have a decidedly important bearing upon the permanence of all engineering structures that cross them.

No undertaking is more vitally concerned with this question than the Catskill aqueduct. Although the principal factors to be taken into account have been considered in other connections [*see* "Faults" and "Folds," pt 1] a unified statement may encourage a more intelligent understanding of the bearing of these structures in southeastern New York on this specific question.

The region included in this discussion extends from the Catskill mountains to New York city. It will be convenient, for the purposes of this argument, to divide the whole area into three districts whose boundaries are determined by decided differences in complexity of geologic history. These lines necessarily follow closely the boundaries of greater stratigraphic unconformities. The youngest groups of strata have suffered only such changes as have accompanied movements of later geologic periods. But before they were formed the underlying groups of rocks were just as profoundly affected by earlier disturbances. In this region, at least, three such groups of large importance exist. The oldest or lowest has been affected by not only everything that has influenced the younger strata but by disturbances of a still earlier time which very much increase their complexity.

On this basis it is convenient to think of the three districts as follows:

A **Catskill district.** Including that portion of the region west and northwest of the Shawangunk mountains and marked by the

prevalence of Siluric and Devonic strata, i. e. all strata above the Hudson River slates. These strata have been affected by only one great mountain-making movement — that of the Appalachian folding, and minor disturbances of still later date.

B **Hudson river district.** This includes that portion of the region lying between the northern border of the Highlands and the Shawangunk mountains. It is marked by the prevalence of Cambric and Ordovicic strata, i. e. Hudson River slates, associated with Wappinger limestone and Poughquag quartzite as the chief bed rock. These strata have been affected not only by the Appalachian folding but also by a still earlier one — that of the Green mountains and the Taconic range. They were folded into mountain ranges and worn down in part again before the Siluric and Devonic strata of district *A* were in existence. Therefore as a structural problem this district (*B*) is approximately twice as complex as the other.

C **Highlands district.** This includes all of the region commonly known as the Highlands of the Hudson as well as the rest of the area south of the Highlands proper to New York city. Its rocks are the oldest — much the oldest. They had been folded into mountain structures and in part worn down before any of the others were accumulated. They have also suffered extensive igneous intrusion so that in places these igneous types prevail. And besides they have been metamorphosed far beyond the point of any other group. No other series of strata has been so profoundly affected. They form the lowest group. All things considered this district should be structurally three times as complicated at the first one (*A*), and adding the igneous and metamorphic complexities, it is probably more near the truth to consider this Highland district four or five times more complex.

All of the formations from the oldest to the Middle Devonic are involved. For the specific formations and their succession and relation the reader is referred to that discussion in part 1 [*see* p. 29. *et. seq.*].

Structural features

Except the most westerly part of the region, that occupied by the Upper Devonic strata, all formations are compressed into folds. Many of the smaller folds, especially those in the Catskill district, are still complete. The easy subdivision of strata possible in this district also simplifies the problem of detecting small changes of attitude. But for the most part the larger folds have been beveled off extensively by surface erosion so that only the truncated limbs

are now to be seen, and the strata therefore appear as narrow belts that dip steeply into the ground. This is more marked in the Hudson river district than in the Catskill, and is still more strikingly true of the Highlands.

There are evidently at least three different epochs of folding interrupting the processes of sedimentation and followed by periods of erosion before sedimentation was again resumed. These breaks constitute so called stratigraphic unconformities and occupy the relative positions indicated in the foregoing tabulated scheme [*see* pt 1].

In each epoch of folding the compressive forces accomplishing this work seem to have acted in a southeast-northwest direction causing successive series of folds with a northeast-southwest trend. The total amount of crustal shortening accompanying these movements is not known, but that it must be many miles is indicated by the fact that the strata of the older series of formations stand prevailingly on edge. All stages between small amount of movement to very great displacement are represented.

Accompanying the folding in each epoch there has been a tendency to rupture and displacement of the "fault" type. There are multitudes of them varying from movements of too little amount to be regarded in a broad way to those of several hundred feet. Most of the larger and more persistent ones are strike faults and follow the main ridges or valleys, sometimes governing the location of escarpments or gorges. Dip faults crossing the formations also occur and doubtless have guided the adjustments of many tributary streams, and occasionally portions of the larger water courses. The thrust fault is most common. This is especially true of the larger ones and particularly those parallel to the trend of the other structural features.

The chief effects of these movements may be summarized as follows:

1 Formations are cut out of their normal order and nonadjacent ones are brought in contact.

2 Cliffs (escarpments) and sharp gulches are more common.

3 Crush zones (belts of brecciated material) are developed.

4 The crush zones give an additional control of stream adjustments.

All of these effects are common. Many of those faults dating back to the earlier epochs are obscure and not readily located. Many of the older weaknesses of this sort have been healed by recrystalli-

zation so that they are now as sound as any other portion of the rock. A good deal depends upon the type of rock and the conditions under which the movement took place. In some of the more open ones, circulating water has seriously affected the rock and in places there is extensive decay even in the harder crystalline formations.

Age of the faulting. The chief epochs of folding and faulting are those of the mountain-making movements — one Precambric, another Postordovicic, and still another Postcarbonic. All of these date very far back in geologic history, and since the last of these, nothing akin to them in importance has been felt in the region.

In Posttriassic times however there was small faulting south of the Highlands, that affected the areas of Triassic rocks of New Jersey and Connecticut.

Whether or not there continued to be slight movement along some of the older lines it is now impossible to say. It is at least clear that all of the great movements belong to very ancient time, and that the last period of geologic time as we know it for this region, has been one of comparative stability. The chief exception is evidently connected with the continental elevations and depressions of the glacial epoch.

Recent movements. The effects of glaciation make it possible to determine whether or not there has been further movement in postglacial time. Conditions are not everywhere favorable enough to detect minute changes, but where they do obtain, the evidence is capable of very definite interpretation. The essential features of these conditions are

1 A bed rock ledge that has been left well smoothed by glacial scouring.

2 Protection from postglacial destruction so that the original unevenness as left by the glacial smoothing can not be mistaken.

If on such a ledge, as now exposed, there are steplike offsets or minute escarpments that could not have remained had they been present during the ice action, then there must have been displacement to this extent, since the original smoothing took place.

A few such evidences have been found in New York and New England, and have been noted in geologic reports. W. W. Mather in his report on the First District of New York (1843) pages 156–57, was the first. The data as now known may be found in the last bulletin of Geologic Papers of the New York State Survey [*see* N. Y. State Mus. Bul. 107 (1907) p. 5–28]. The following para-

graphs are intended as a brief summary and comment on the facts as there given:

Localities where some postglacial displacement has been detected.

1 Copake, N. Y., on the eastern border of the State near the southwest corner of Massachusetts

2 Rensselaer, N. Y.

3 South Troy, N. Y.

4 Defreestville, N. Y. (near Troy)

5 Pumpkin Hollow, N. Y. (near Copake)

6 Kilburn Crag, N. H.

7 Port Kent, N. Y. (uncertain)

8 Attleboro, Mass.

In addition to these there is reference to similar occurrences at St John, N. B. and in the province of Quebec. All of the known localities lie a considerable distance beyond, north and northeast, of the Catskill aqueduct line.

Causes of displacement. In southern New York all of the cases of postglacial faulting yet discovered lie in the area of slates belonging to the Hudson River series. Whether the belt now occupied by this formation is therefore to be considered the most unstable zone, or whether there is some tendency to slight readjustment inherent in the slates themselves causing these movements, is not clear. It would seem consistent with known recent geologic history to connect these displacements with the general elevation and subsidences accompanying and following the glacial occupation. It is perfectly clear that the whole continental border in this region suffered considerable subsidence during glacial time. Also the terraces and deposits along the Hudson prove beyond question that during the ice retreat, at the very close of the glacial occupation, the land surface stood from 80 to 150 feet lower than now. Therefore an elevation of this amount has occurred in postglacial time, and probably, judging from the condition of the terraces themselves, took place soon after the glacial ice withdrew.

The stresses and inevitable warpings accompanying these mass movements seem to be sufficient to account for all displacements known to be of this age. There is nothing in them that necessarily promises a renewal of mountain folding. But it appears that the movements have almost all been of the thrust character and in this respect they differ not at all from the commoner type of the region.

Amount of displacement. The greatest throw noted on any single Postglacial fault in eastern New York is given by Woodworth as 6 inches, and he remarks that this is imperfectly shown. Usually the displacement is distributed over a zone in which several small faults occur instead of a single larger one. This may mean that the whole disturbance is essentially superficial.

At South Troy it is stated that a total displacement of 12 inches is thus distributed through a number of small faults within a distance of 30 feet.

At Rensselaer a total of 5 inches is given.

At Defreestville a total of 13 inches is indicated in a distance of 11.67 feet.

At Copake, at two different spots, a total of more than 7 inches was measured within a space of 12 feet. Woodworth thinks that the total displacement for the locality may exceed 2 feet.

At Pumpkin Hollow a total of 17 inches is estimated.

Conclusion. If such rates prevail over larger areas beneath the drift, it is clear that rather profound changes would be indicated. But thus far there is no indication of such continuity.

Likewise if it were certain that the movements are now in progress, it would be a matter of greater concern. But there is no direct evidence to prove it.

Estimates of the length of postglacial time differ greatly. The shortest ones worthy of consideration range from about 5000 to 10,000; the longest run above 100,000 years.

Some intermediate value is probably nearer the truth — say 25,000 years.

Adjusting the postglacial faulting problem then to these time estimates the summary of it all would be as follows: Somewhere within postglacial time, i. e. approximately 25,000 years, movements of strata have developed at a few places in eastern New York that appear as small faults with total throw in each locality varying from a few inches to perhaps as much as 2 feet. Whether the movement has been gradual and continuous or concentrated largely into sôme small portion of this time is not known. Whether the effects are extensive or, on the contrary, very local and superficial, is likewise unknown. But in any case there are no known instances of violent and large displacements, such as would be likely to cause great damage to sound structures, in this region in postglacial time.

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